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DYNAMO-ELECTRIC MACHINERY:

A MANUAL FOR STUDENTS OF ELECTROTECHNICS.

BY

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FELLOW OF THE ROYAL ASTRONOMICAL SOCIETY.

FOURTH EDITION, ENLARGED AND REVISED.

FROM NEW AMERICAN TYPE SET PLATES.

VOL. I

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PREFACE

TO THE FOURTH EDITION.

In this fourth edition, which has been very largely rewritten, there are several features which distinguish it from its predecessors.

The great development of public electric lighting during the past five years has necessitated the construction of very large dynamos suitable for central stations. Of the established types of these machines detailed descriptions are given.

A number of Plates have been added, some of them being scale-drawings of recent forms of machines.

The invention of alternate-current motors of many novel types, depending on the production of multiphase alternate currents, has claimed a special chapter.

A chapter has been added on the theory of armature winding.

No pains have been spared to ascertain the most approved practice in the construction of armatures, commutators, and other details requiring combined mechanical and electrical knowledge and experience. A chapter has been added on dynamo design.

Transmission of power by electrical means also claims a short special chapter.

Some remarks on the management of dynamos have been embodied at the end of the work.

It would have been impossible to do justice to the present development of the subject but for the co-operation of the electrical engineers and engineering firms who are leading the advance. For such co-operation the author's thanks are gratefully given. And in particular he tenders his acknowledgment to the following, who have specially aided him by furnishing him with drawings and statistical data: Mr. C. E. L. Brown (late of the Oerlikon Works, Zürich); Mr. Gisbert Kapp; Mr. W. B. Esson (of Messrs. Paterson and Cooper); Mr. Mordey (Brush Electric Engineering Co.); Mr. T. Parker (Electric Construction Corporation); Mr. Albion T. Snell (General Electric Traction Co.); Messrs. W. T. Goolden and Co.; Mr. S. Z. de Ferranti; Messrs. Blakey, Emmott and Co.; The Gülcher Electric Co.; Messrs. Ernest Scott and Co.; Messrs. J. H. Holmes and Co.; Messrs. Siemens Bros.; Messrs. Mather and Platt; Messrs. R. E. Crompton and Co.; Messrs. S. Schuckert and Co.; Messrs. J. G. Statter and Co.

For the use of cuts the author is indebted to various of the above-named firms, and also to the publishers of the following journals: *The Electrician*, *Electrical Review*, *Industries*, and *La Lumière Electrique*. To the publishers of the *Electrical Engineer* (N. Y.) for Plate XIII.

The author is indebted to his colleague, Professor Perry, F. R. S., for the use of some of his notes in the preparation of Chapter XV.

His former chief assistant, Professor R. Mullineux Walmsley, has again kindly rendered help in reading proofs of several of the new chapters.

To his late pupil, Mr. Walter Hawkins, the author is indebted for valuable help in preparing drawings, particularly those dealing with armature winding.

Heavy as the task is of adequately presenting the principles and practice of a department of science which has undergone such an enormously rapid development, that task has been lightened in three directions by the circumstance that three fellow-workers in science have lately devoted themselves to expounding special branches of it. Professor Ewing, of whose researches in magnetism an all too brief account has been given in this book, has prepared a treatise on magnetism which is on the very eve of publication. Professor Fleming has already published the first half of a treatise on the Alternate Current Transformer, and the second half will soon appear. Mr. Gisbert Kapp's work on Electric Transmission of Power has already commanded a wide acceptance. There has been, therefore, the less necessity to extend those chapters in the author's book which deal with these topics, though they have been carefully brought up to date.

Want of space has precluded the author from treating as fully as he would have desired the topic of central station machinery. This has assumed three different types in England, Germany, and America. In England, engineers have developed special forms of high-speed engine to be coupled direct to the dynamo. In Germany practice has taken the inverse course of designing huge slow-speed dynamos for attachment direct to engines of older type. Either of these methods is, in the author's opinion, preferable to the American practice of building high-speed dynamos and low-speed engines, and then connecting them by belts running over pulleys.

It would be difficult to discover any scientific subject which more thoroughly illustrates the principle of action and reaction than does this of dynamo-electric machinery. In every department of the subject the essential thing to be understood is a reaction of some sort. In the rotating armature of the dynamo the very production of the current sets up an opposing drag, and the work of generating the current is done by driving the machine against this mechanical reaction. In the motor the very production of motion sets up an opposing electromotive-force which tends to stop the supply of current. In the transformer, the current which is set up by the magnetic changes in the core, tends to oppose those changes. In the self-induction coil the changes of magnetism which result from the impressed waves of current tend to destroy those waves. In the alternate-current motor the moving part tends so to move as to annul the changes of magnetic polarity which urge it round. In the classical law of magneto-electric action, formulated by Lenz, it is declared that an induced current is always such that by virtue of its electromagnetic effect it tends to stop the motion which generated it. To this we have added (p. 589) a converse and equally general law for electric motor action, namely, that the motion produced is always such that by virtue of the magneto-electric inductions which it sets up it tends to stop the current. Both are but forms of a still more general law applicable to every electromagnetic system, namely, that every action on such a system which, in producing a change in its configuration or state involves a transfer of energy, is resisted by reactions tending to preserve unchanged the configuration or state of that system.

The subject of dynamo-electric machinery is, however something more than a mere branch of universal dynamics; it constitutes to-day a very active department of constructive engineering. To set forth this practical side of the subject in a manner useful to engineers has been the author's continual aim.

S. P. T.

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DYNAMO-ELECTRIC MACHINERY.

CHAPTER I.

INTRODUCTORY.

A dynamo-electric machine is a machine for converting energy in the form of mechanical power into energy in the form of electric currents, or vice versâ, by the operation of setting conductors (usually in the form of coils of copper wire) *to rotate in a magnetic field.* This definition is framed to include all machines, the action of which is dependent on the principle of magneto-electric induction, discovered by Faraday in 1831.

Every dynamo-electric machine is, however, capable of serving two distinct functions, the converse of one another. When supplied with mechanical power from some external source of power, such as a steam engine, it furnishes electric currents. When supplied with electric currents from some external source such as a voltaic battery, it furnishes mechanical power. On the one hand the dynamo serves as a *generator*, on the other hand as a *motor*. All dynamos, however, belong to one of two great sub-divisions, being distinguished, according to the nature of the current which they are to supply, whether *direct* (*i. e.* uni-directional in flow) or *alternating* (*i. e.* rapidly reversing the direction of the flow). We shall therefore have to consider four classes of machines —(*a*) direct-current dynamos; (*b*) alternate-current dynamos, or, briefly, alternators; (*c*) direct-current motors; (*d*) alternate-current motors. In general every dynamo, whether intended for use as a generator or as a motor, consists of two essential parts, a *field-magnet*, usually a massive, stationary structure of iron surrounded by coils of insulated copper wire, and an *armature*, a peculiarly arranged system of copper conductors, usually wound upon the periphery of a ring, drum, or disk, fixed upon a shaft whereby rotation can be imparted mechanically. There are also special devices for receiving the electric currents from the armature and imparting them to the electric circuit, or *vice versâ*, known as *collectors* or *commutators*, attached to the armature and rotating with it, and collecting *brushes*, constituting sliding circuit connexions, which press upon the moving surface of the collector or commutator.

The function of the field-magnet is to provide a *magnetic field* of great extent and intensity; that is to say, to provide an enormous number of lines of magnetic force in the space wherein the armature conductors are to revolve. It must consequently consist of a large and well-designed, and therefore powerful, magnet or electromagnet, having its poles so shaped that the magnetic lines that issue from them shall be utilised in the armature space. The magnetic field and the magnetic properties of iron are dealt with in Chapter VI.; the fundamental principles of the magnetic circuit, including the designing of field-magnets, are dealt with in Chapters VII., VIII., and XVI.

The function of the armature is to rotate in the magnetic field, whilst carrying electric currents in its copper coils or conductors.

It must be remembered that there is a two-fold action between a conducting wire (forming part of a circuit) and a magnetic field. *Firstly*, if the conducting wire is forcibly moved across the magnetic field (so as to cut across the magnetic lines), electric currents are generated in the conductor, and a mechanical effort is required to move the conductor. This action, discovered by Faraday, is termed "magneto-electric induction." In every case the induction or generation of currents necessitates the application of mechanical power and the expenditure of energy. This is the principle of the dynamo used as a generator. *Secondly*, if the conducting wire, while situated in the magnetic field, is actually conveying an electric current (from whatever source) it experiences a lateral thrust, tending to move it forcibly, parallel to itself, across the magnetic lines, and so enables it to exert power and to do work. This action, which is the converse of the former, is the principle of the dynamo used as a motor. In the first case power is required to drive the armature; in the second, the armature rotating becomes a source of power. If we have the magnetic field, and supply power to drive the rotating conductor, we get the electric currents; if we have the magnetic field and supply the electric currents to the conductor, it rotates and furnishes power. Whether the machine be used as generator or as motor, the magnetic field must be present: hence the most important point in theory is the theory of the magnetic field. As every dynamo will work (at least theoretically) either as generator or as motor, it should be possible to frame a general theory for any machine serving either of the two converse functions. For the sake of simplicity, however, these two functions will be separately considered in the present work.

The mathematical theory of the dynamo is, indeed, complex, and takes different forms for its expression in the various classes of machine now included under the one name of "dynamo." The progress recently made in the theoretical treatment of magnetic problems has simplified matters so much that it is now possible to predict from the construction and dimensions of a dynamo its electrical output under given conditions of speed and load. The theory of alternate-current machines is different in many points from that of machines which are to furnish continuous currents. The theory of the dynamo, then, which will be developed in the present work, will not be a general mathematical theory. The aim will be to deal with physical and experimental rather than mathematical ideas, though of necessity mathematical symbols must be used here as in every kind of engineering work. A physical theory of the dynamo is not new, though none of any great completeness had been given[1] prior to the appearance of the author's lectures at the *Society of Arts* in 1882.

There are, in fact, three distinct methods of dealing with the principles of the dynamo: (1) a physical method, dealing with the lines of magnetic force and with currents, in which these quantities are made, without further inquiry into their why or how, the subjects of the arguments; (2) an algebraical method, founded upon the mathematical laws of the electric induction and of theoretical-mechanics; and (3) a graphical method, based upon the possibility of representing the action of a dynamo by a so-called "characteristic" curve, in the manner originally devised by Dr. Hopkinson, and subsequently used by Frölich, Deprez, and others.

These three methods present three aspects of the same thing. The number of lines of magnetic force, with which we deal in Chapter VI. and VII., may be expressed by a certain length of line geometrically, or by the symbol N algebraically, or they may be represented pictorially by a mere illustration. What some people write N for, other people indicate by drawing a line of a certain length in a certain direction. We approximate, in fact, toward understanding the whole truth by various processes: sometimes by algebra; sometimes by geometry; sometimes by magnetic diagrams; and each of these processes is of value in its turn.

It will be our aim first briefly to develop a general physical theory, applicable to all the varied types of dynamo-electric machines. Then we shall at once plunge into the most fundamentally important matter; the principle of the magnetic circuit; the magnetic properties of iron; the design of the magnetic parts of dynamos, and the like. After this will come the theory of armature winding, and practical modes of construction. This will be followed by a general descriptive account of the various types of machines, and by various matters of theoretical interest. The direct-current motor will be considered after the direct-current generator. The special topics of the alternate-current dynamo, the alternate-current transformer, and the alternate-current motor, are treated in fuller detail than in any of the previous editions of this work.

---

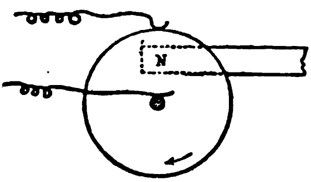
[1] See J. M. Gaugain, *Annales de Chimie et de Physique*, 1873; Antoine Breguet, *Annales de Chimie et de Physique*, 1879; Du Moncel, *Exposé des Applications de l'Electricité*, vol. ii.; Niaudet, *Machines Electriques;* Dredge's *Electric Illumination;* Schellen, *Die Magneto-und Dynamo-elektrischen Maschinen* (3rd edition, 1883).

Before, however, proceeding to the general theory of the dynamo, it will be expedient to introduce a few historical notes.

CHAPTER II.

HISTORICAL NOTES.

FIG. 1.



FARADAY'S DISK DYNAMO.

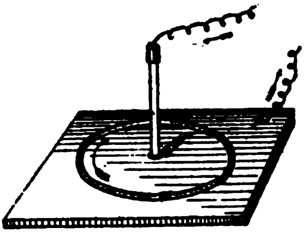
FARADAY'S discovery of the magneto-electric induction of currents was made in the autumn of 1831, and communicated, on Nov. 24th, to the Royal Society in a paper printed in the *Philosophical Transactions*, and reprinted in the beginning of the first volume of Faraday's *Experimental Researches in Electricity*. His first experiments related to the production of induced currents in a coil by means of currents started or stopped in a neighbouring coil; from these he went on to currents generated in a coil moved in front of the poles of a powerful steel magnet. Upon thus obtaining electricity from magnets he attempted to construct "a new electrical machine." A disk of copper, 12 inches in diameter (Fig. 1), and about one-fifth of an inch in thickness, fixed upon a brass axle, was mounted in frames, so as to allow of revolution, its edge being at the same time introduced between the magnetic poles of a large compound permanent magnet, the poles being about half an inch apart.[1] The edge of the plate was well amalgamated, for the purpose of obtaining a good but movable contact, and a part round the axle was also prepared in a similar manner. Conducting strips of copper and lead to serve as electric collectors, were prepared, so as to be placed in contact with the edge of the copper disk; one of these was held by hand to touch the edge of the disk between the magnet poles. The wires from a galvanometer were connected, the one to the collecting-strip, the other to the brass axle; then on revolving the disk a deflexion of the galvanometer was obtained, which was reversed in direction when the direction of the rotation was reversed. "Here, therefore, was demonstrated the production of a permanent current of electricity by ordinary magnets." These effects were also obtained from the poles of electromagnets, and from copper helices without iron cores. Several other forms of magneto-electric machines were tried by Faraday.

---

[1] *Experimental Researches*, i. 25, art. 85. This piece of apparatus is still preserved at the *Royal Institution*. It was shown in action by the author of this work at a lecture at the Royal Institution delivered April 11th, 1891.

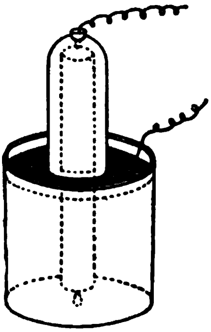
In one,[1] a flat ring of twelve inches external diameter, and one inch broad, was cut from a thick copper plate, and mounted to revolve between the poles of the magnet, two conductors being applied to make rubbing contact at the inner and outer edge at the part which passed between the magnetic poles. In another,[2] a disk of copper, one-fifth of an inch thick, and only 1½ inch in diameter (Fig. 2), was amalgamated at the edge, and mounted on a copper axle. A square piece of sheet metal had a circular hole cut in it, into which the disk fitted loosely, a little mercury completed communication between the disk and its surrounding ring. The latter was connected by wire to a galvanometer; the other wire being connected from the instrument to the end of the axle. Upon rotating the disk in a horizontal plane, currents were obtained though the earth was the only magnet employed.

Fig. 2.



Faraday's Teetotum Apparatus.

Fig. 3.



Faraday's Rotating Copper Cylinder.

Faraday also proposed a multiple machine[3] having several disks, metallically connected alternately at the edges and centres by means of mercury, which were then to be revolved alternately in opposite directions. In another apparatus[4] a copper cylinder (Fig. 3), closed at one extremity, was put over a magnet, one-half of which it enclosed like a cap, and to which it was attached without making metallic contact. The arrangement was then floated upright in a narrow jar of mercury, so that the lower edge of the copper cap touched the fluid. On rotating the magnet and its attached cap, a current was sent through wires from the mercury to the top of the copper cap. In another apparatus,[1] still preserved at the Royal Institution, a cylindrical bar magnet, half immersed in mercury, was made to rotate, and generated a current, its own metal serving as a conductor. In another form,[2] the cylindrical magnet was rotated horizontally about its own axis, and was found to generate currents which flowed from the middle to the ends, or *vice versâ*, according to the rotation. In yet another machine (Fig. 4) constructed by Faraday some time later,[3] a simple rectangle of copper wire, attached to a frame, was rotated about a horizontal axis placed east and west, and generated alternate currents, which could be collected by a simple commutator.

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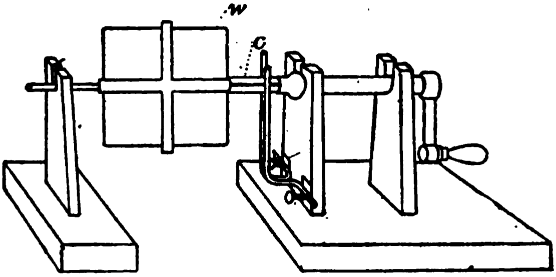
[1] *Experimental Researches*, i. art. 135.

[2] *Ib.*, art. 155.

[3] *Ib.*, art. 158.

[4] *Ib.*, art. 219.

FIG. 4.



FARADAY'S ROTATING RECTANGLE.

Within a few months machines on the principle of magneto-induction had been devised by Dal Negro,[4] and by Pixii.[5] In the latter's apparatus a steel horseshoe magnet with its poles upwards, was caused to rotate about a vertical shaft, inducing alternate currents in a pair of bobbins fixed above it, and provided with a horseshoe core of soft iron. Later, in 1832, Pixii produced, at the suggestion of Ampère,[6] a second machine, provided with commutators to rectify the alternating currents. Further improvements were made by Ritchie[7] and Watkins.[8] In 1833 appeared the machine of

---

[1] *Experimental Researches*, i. art. 220. [2] *Ib.*, art. 222. [3] *Ib.*, art. 3192.

[4] *Phil. Mag.* [3] i. 45, July 1832 (an oscillatory apparatus).

[5] *Ann. Chim. Phys.* i. 322, 1832. [6] *Ann. Chim. Phys.*, li. 76, 1832.

[7] *Phil. Mag.* [3] viii. 455 ; [3] x. 280, 1837 ; and *Phil. Trans.*, ii. 318, 1833.

[8] *Phil. Mag.* [3] vii. 107, 1835.

Saxton,[1] and two years later that of Clarke;[2] both having the steel horseshoe magnet a fixture, and having as a revolving armature an electromagnet consisting of a pair of bobbins wound upon a simple horseshoe of iron. Clarke's machine possessed many original details, including a special form of commutator for giving short, sharp currents for physiological purposes. In it the armature rotated, not opposite the ends, but in close proximity to the flat faces of the magnet. In Saxton's machine, which was shown to the British Association at Cambridge in 1833, the armature was rotated opposite the polar ends, and consisted of four coils. Von Ettingshausen,[3] in 1837, brought out a very similar alternate-current machine, with a special device by which the alternate currents could be cut out. Poggendorff,[4] in 1838, devised a special mercury-cup commutator for Saxton's machine, to make the currents less discontinuous.

Other improvements in detail were made by Petrina,[5] who improved the commutator; Jacobi,[6] who pointed out the importance of using short cores for the armatures; Sturgeon,[7] who placed a shuttle-wound coil longitudinally between the limbs of a horseshoe magnet, and who also invented the simple two-part commutator or "unio-directive discharger," as he termed it; Stöhrer,[8] who showed how to construct a six-pole machine with six bobbins in the armature; Ritchie,[9] who employed tubular cores and a double winding; and Pulvermacher,[10] who in 1849 proposed the use of thin laminæ of iron as core-plates. Woolrich,[11] in 1841, devised a multipolar machine for electroplating, having twice as many rotating coils as magnet-poles. Wheatstone[12] began his improvements in 1841, with a machine in which for the first time the armature coils were so grouped as to give a really continuous current (Fig. 5). For this purpose five armatures, each consisting of a pair of short parallel cylindrical coils with iron cores, and each having a simple split-tube commutator, were arranged in a row along a single shaft, with six compound steel magnets between them, the five armatures being so set that they came successively into the position of greatest activity, no two of them being commuted at the same instant. They were connected in series with one another by wires, which joined the positive brush—a brass spring—of one to the negative brush of the next. In 1845 Wheatstone[1] and Cooke patented the use of electromagnets instead of steel permanent magnets in such machines. In 1848 Jacob Brett[2] made the important suggestion of causing the current developed in the armature by the permanent magnetism of the field-magnets to be transmitted through a coil of wire surrounding the magnet, so as to increase its action. This suggestion, which appears to be the first suggestion of the principle of

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[1] *Phil. Mag.* [3] ix. 360, 1836.

[2] *Phil. Mag.* [3] ix. 262, 1836; x. 365, 455, 1837; and Sturgeon's *Annals of Electricity*, i. 145.

[3] Gehler's *Physikalisches Wörterbuch*, ix. 122, 1838.

[4] *Pogg. Ann.*, xlv. 385, 1838.

[5] *Pogg. Ann.*, lxiv. 58, 1845.

[6] *Pogg. Ann.*, lxix. 194, 1846.

[7] *Annals of Electricity*, ii. 1, 1838. See also Sturgeon's *Scientific Researches*, p. 252; also *Phil. Mag.*, vii. 231, 1835.

[8] *Pogg. Ann.*, lxi. 417, 1884; lxxvii. 467, 1849.

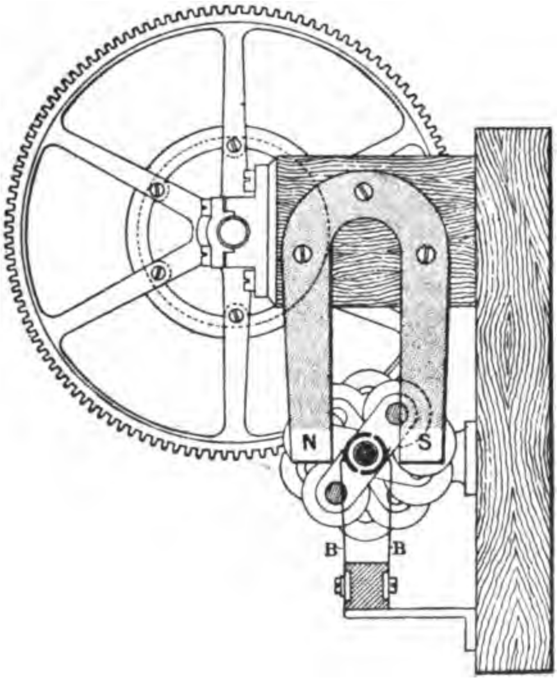
[9] Specification of Patent, 14,899 of 1849.

[10] *Loc. cit.*

[11] See also Specification of Patent, 9431 of 1842.

[12] Specification of Patent, 9022 of 1841.

FIG. 5.



WHEATSTONE'S CONTINUOUS-CURRENT MACHINE.

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[1] Specification of Patent, 10,655 of 1845.
[2] Specification of Patent, 12,054 of 1848.

the self-exciting dynamo, was independently made in 1851 by Sinsteden,[1] who appears to have had full knowledge of the fact, investigated by Müller, that steel is capable of receiving a temporary magnetization not greatly inferior to that of wrought iron, and far in excess of that which it can permanently retain. Sinsteden's researches were numerous and important, relating to the best width of polar surface to employ, to the use of pole-pieces, and to the lamination of armature cores, for which purpose he employed, in 1849, iron wire bundles. A quite different type of machine was suggested independently by Ritchie,[2] by Page,[3] and by Dujardin,[4] in which neither field-magnet nor armature rotated; the coils in which the currents were to be induced were wound upon polar extensions of the field-magnets, and the induction was produced by rotating in front of them pieces of soft iron, which set up rapid periodic variations in the magnetic field. Machines on this same principle were later devised by Holmes, Henley, Wheatstone, Wilde, Sawyer, by the author of this work, and by Kingdon.

Nollet,[5] in 1849, devised an alternate-current machine, in the construction of which he was joined by Van Malderen; and after the death of Nollet this was developed, with the aid, first of Holmes, then of Masson and Du Moncel, into the "Alliance" [6] machine, which, from the year 1863, did good service in the lighthouses of France. Holmes continued to perfect his work, and produced a fine machine,[7] which in 1857 received high commendation from Faraday. The great machine of Holmes shown in the International Exhibition of 1862, was a continuous-current machine, with a large commutator and rotating rollers for brushes; the bobbins, 160 in number, were arranged on the peripheries of two wheels, each about 9 ft. in diameter. There were sixty horseshoe magnets arranged in three circles, each presenting radially forty poles. In 1867 Holmes remodelled his machine, making the field-magnets more powerful in proportion, and leaving the induced currents uncommuted; and in 1869 he introduced the principle of diverting the current from a few of the armature coils, through a commutator, to excite the field-magnets. This period was one of great activity. In 1855 Hjorth[1] patented a remarkable machine, having for its field-magnets a compound arrangement of a permanent magnet to provide initial currents, and powerful electromagnets to be excited up by the currents generated by the machine itself.

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[1] *Pogg. Ann.*, lxxxiv. 186, 1851. For Sinsteden's other researches see *Pogg. Ann.*, lxxvi. 29, 195 and 524, 1849; lxxxiv. 181, 1852; xcii. 1 and 220, 1854; xcvi. 353, 1855; cxxxvii. 290 and 483, 1869.

[2] *Phil. Mag.* [3] x. 280, 1837.

[3] *Annals of Electricity*, 489, 1839.

[4] *Comptes Rendus*, xviii. 837, 1844; xxi. 528, 892, 1881.

[5] See Specification of Patent, 13,302 of 1850. See also Douglass in *Proc. Inst. Civil Engin.*, lvii. 1878–9.

[6] See Du Moncel's *Exposé des Applications de l'Electricité*, i. 361. Also see Le Roux, *Bulletin de la Société d'Encouragement*, 1868.

[7] See Douglass, *loc. cit.* Also Specifications of Patents, 573 of 1856, 2060 of 1868, and 1774 of 1869.

C. W. Siemens[2] in 1856 provisionally patented the famous shuttle-wound longitudinal armature, invented by Werner Siemens. In 1859,[3] he made the suggestion that the core only need rotate, the coils being fixed in grooves in the pole-pieces of the field-magnets. Wilde,[4] of Manchester, embarked on a remarkable series of researches from 1861 to 1867. Beginning with small apparatus for telegraphic purposes, he was led in 1863 to devise an apparatus having a shuttle-wound Siemens armature between the poles of a powerful electromagnet, the coils of which were traversed by currents furnished by a small auxiliary machine—with shuttle-wound armature and permanent magnets—mounted upon its summit. In 1866 and 1867 Wilde devised alternate-current machines, of which the latest had a number of bobbins mounted on the periphery of a disk rotating between two opposite crowns of alternately polarized field-magnets—a type which survives to the present day. These machines, originally separately excited by currents from a small magneto machine, were made self-exciting, in 1873, by diverting through a commutator the currents induced in one or more of the armature bobbins. The principle of using the whole or part of the machine's own currents to excite the requisite magnetism of its field-magnets was by this time becoming recognized. As mentioned above, Brett, Sinsteden, and Hjorth had all made use of this principle. In 1858, Johnson,[5] patent-agent for a foreign inventor, states: "It is proposed to employ the electromagnet in obtaining induced electricity, which supplies wholly or partially the electricity necessary for polarizing the electromagnets, which electricity would otherwise be required to be obtained from batteries or other known sources." In July, 1866, Murray[1] stated that he had connected in series with the armature some coils wound on the field-magnets of his magneto machine and recommended the adoption of this plan. In October, 1866, Moses G. Farmer[2] wrote to Wilde of Manchester, describing his success in winding main circuit coils upon the field-magnets of his machine, so as to cause it to excite its own magnets. In November, 1866, Baker[3] stated that the secondary currents from the revolving magnets might be applied to magnetize the fixed magnets. In December of the same year C. and S. A. Varley[4] filed a Provisional Specification for a machine having electromagnets only, which apparatus, however, required before using to have given to it a small amount of permanent magnetism since the inventors state that "the bobbins become slightly magnetized in their passage between the poles of the permanent magnets." This, it must be conjectured, was given to it by passing an electric current through the coils of the electro-magnets; a device which reappears in another machine patented by the same inventors in June, 1867, and again in another by O. and F. H. Varley in 1869. The electromagnets of the 1867 machine were wound with two separate circuits, supplied alternately with currents from two commutators which received the currents from two separate pairs of coils. Mr. S. A. Varley continued, in 1868, and 1871, to patent magneto-electric generators. In 1876 he returned to the self-exciting method, employing a multiple armature in which the principle was applied of cutting out each coil in succession during the rotation. In this machine also there were two windings on the field-magnets, one of greater resistance than the other, both of which were led to the lamp, the circuit of greater resistance being always closed. It was not, however, clear that this method of double winding was what is now understood as "compound winding,"[5] until such was laid down with legal authority by a Scotch judge fifteen years later. Returning to the self-exciting principle, we find that on January 17th, 1867, Dr. Werner Siemens[6] described to the Berlin Academy a machine for generating electric currents by the application of mechanical power, the currents being induced in the coils of a rotating armature by the action of electromagnets, which were themselves excited by the currents so generated. In this machine also initial permanent magnetism was to be given by sending a preliminary current through the coils from a battery. To mark the importance of this departure Siemens coined the name *dynamo-electric machine*, which now, in the shortened form of *dynamo*, has become the familiar term for all these electric machines driven by mechanical power, whether self-excited or not. On the same day that this discovery was announced to the Royal Society, February 14th, 1867, a paper was read by Sir C. Wheatstone,[1] making an almost identical suggestion; but with this difference, that whilst Siemens proposed that the exciting coils, should be in the main circuit, in series with the armature coils Wheatstone proposed that they should be connected as a shunt. A self-exciting machine without permanent magnets had indeed been constructed for Wheatstone by Mr. Stroh in the summer of 1866.

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[1] Specifications of Patents, 12,295 of 1848, 2199 of 1854, 2198 of 1854, 806 of 1855, 807 of 1855, and 808 of 1855.

[2] Specification of Patent, 2017 of 1856. See W. Siemens, *Pogg. Ann.*, ci. 271, 1857.

[3] Specification of Patent, 512 of 1859.

[4] Specifications of Patents, 299, 858, 1994 and 2997 of 1861; 516 and 8006 of 1863, 1412 and 2753 of 1865, 3209 of 1866, and 824 of 1867.

[5] Specification of Patent, 2676 of 1858.

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[1] See *Engineer*, p. 42, July 20, 1866.

[2] *Proc. Lit. and Phil. Soc. of Manchester*, vi. 107.

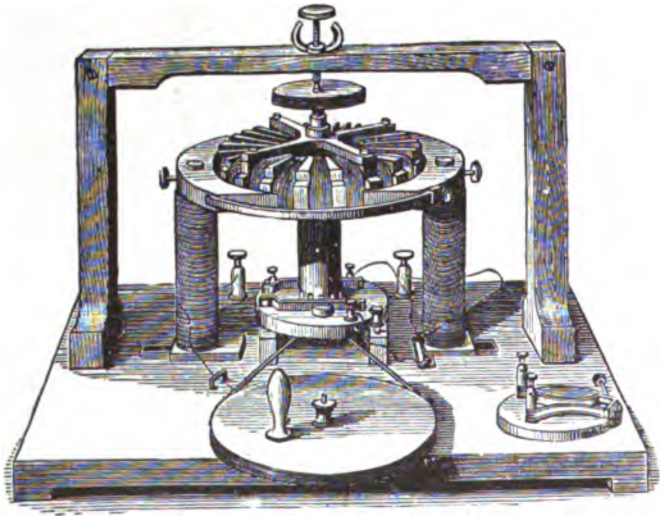
[3] Specification of Patent, 3039 of 1866.

[4] Specification of Patent, 3394 of 1866. Other Varley Specifications are 1755 of 1867, 315 of 1868, 131 and 1150 of 1871, 4905 of 1876, 270 and 4435 of 1877, 4100 of 1878.

[5] See *Phil. Mag.* [4] xlv. 439, 1873.

[6] *Berliner Berichte*, Jan. 1867 ; *Proc. Roy. Soc.*, Feb. 14, 1867; Specification of Patent, 261 of 1867; and *Pogg. Ann.* cxxx. 332, 1867.

FIG. 6.



PACINOTTI'S MACHINE, WITH RING ARMATURE.

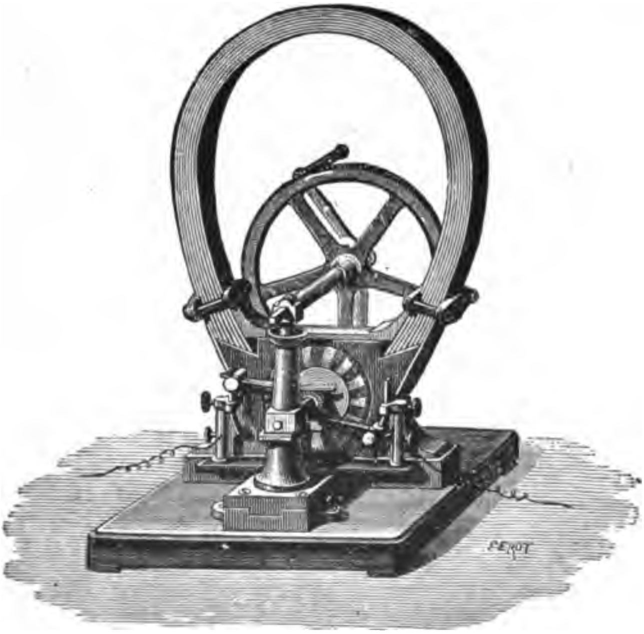
In 1867 Ladd[2] exhibited a self-exciting machine having two shuttle-wound armatures, a small one to excite the common field-magnet, a large one to supply currents for electric light.

[1] *Proc. Roy. Soc.*, Feb. 14, 1867.

[2] *Phil. Mag.* [4] xxxiii. 544, 1867.

Meantime the question of procuring continuous currents, with less fluctuation in their strength, had come up, and had received from Pacinotti[1] an answer, which, though it fell into temporary oblivion, is now recognized as of great merit. He devised a machine, first described in 1864, having as its armature an electromagnet in the form of a ring, the core consisting of a toothed iron wheel, between the teeth of which the coils were wound in sixteen separate sections. He denominated this a "transversal electromagnet." The coils being joined up in a closed circuit, if at any point a current was introduced, it flowed both ways through the coils to some other point where it was taken off by a return wire. By the device of leading down connections, at sixteen different points around the ring, to sixteen insulated pieces of metal arranged as a commutator, it was possible to cause magnetic poles to appear in the ring at any desired points. The principle of winding a continuous coil in separate symmetrical sections around a ring, or other figure of revolution,

FIG. 7.



GRAMME MACHINE, LABORATORY PATTERN.

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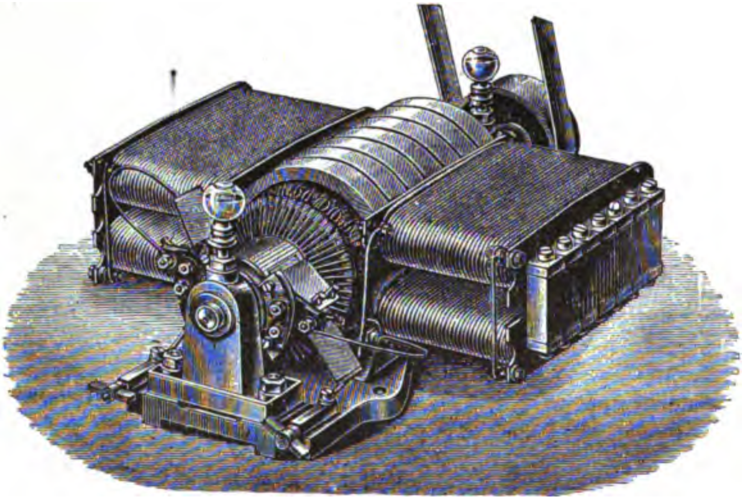
[1] *Nuovo Cimento*, xix. 378, 1865.

was independently invented, in 1870, by Gramme,[1] whose ring had no teeth, and was entirely overwound with wire. By winding an armature with a number of such symmetrically grouped coils which pass successively through the magnetic field, currents can be obtained that are practically steady. The introduction of the Gramme armature was at once recognized as marking an important step, and it gave a fresh impetus to invention. In 1873 von Hefner Alteneck[2] modified the longitudinal armature of Siemens by covering it with windings spaced out at symmetrical angles to secure the same advantage of continuity, and Lontin[3] in 1874 sought to perform a like transformation upon an armature with radiating poles. Gramme and Siemens both devised many special forms of machines, some furnishing alternating currents,[4] others continuous currents. Bertin in 1875, Brush in 1879, and Siemens,[5] in 1880, revived the method of shunt-winding.

FIG. 8.



SIEMENS'S DYNAMO WITH VON HEFNER ALTENECK'S DRUM-WOUND ARMATURE.

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[1] *Comptes Rendus*, lxxiii. 175, 1871, and lxxv. 1497, 1872; and Specification of Patents, 1668 of 1870.

[2] Specification of Patent, 2006 of 1873. A similar suggestion had been thrown out the previous year by Worms de Romilly.

[3] Specifications of Patents, 473 of 1875, 386 and 3264 of 1876.

[4] Specification of Patents, Gramme, 953 of 1878; Siemens, 3134 of 1878.

[5] *Phil. Trans.*, March 1880.

In 1878 Pacinotti[1] devised a kind of armature in which the conductors took the form of a flat disk or fly-wheel. Brush[2] also introduced his famous dynamo embodying the principle of open-coil working. He also introduced the simultaneous use of a shunt and a series winding for the purpose of enabling the machine to do either a large or a small amount of work. Another open-coil machine was introduced in 1880 by Elihu Thomson and E. J. Houston,[3] of Philadelphia. About the same time Weston[4] devised several forms of dynamo, and in particular developed shunt-wound machines. Many other American inventors produced dynamos, amongst them Edison,[5] who began in 1878, with a machine in which the motion was oscillatory instead of rotatory, a device which had been tried by Dujardin,[6] in 1856, by Siemens,[7] in 1859, by Wilde,[8] in 1861, and abandoned. Edison himself abandoned it in 1879 for a form of machine having a modified Hefner-Alteneck armature and an elongated shunt-wound electromagnet. In 1881, he produced a disk dynamo on the same lines as Pacinotti's disk. The same year saw a revival of alternate-current machines in the forms devised by Sir. W. Thomson[9] (and independently by Ferranti) and Gordon.[10]

About this time multipolar dynamos began to come into favour, the multipolar drum armature introduced by Lord Elphinstone[11] and Mr. Vincent, and the multipolar ring, independently, by Schuckert, Gramme, Gülcher, and Mordey.[12] Lord Elphinstone in particular drew attention to the importance of perfecting the magnetic circuit, though, for purely mechanical reasons, his machine soon became obsolete. Hopkinson[13] showed how greatly the performance of a dynamo was improved by improving and making more compact its magnetic circuit, whilst Crompton[14] amidst a number of improvements in detail, showed the advantage of increasing the cross-section of iron in the armature core. Meantime theoretical considerations had led Marcel Deprez,[1] in 1881, to the conclusion that a dynamo driven at a certain critical speed ought to be able to distribute currents at a constant potential if its field-magnets were provided with a second coil to furnish from a battery or other source an independent and constant auxiliary excitation. This was almost immediately followed by the general adoption of the so-called compound winding, for the purpose of obtaining a self-regulating dynamo, this advance being the subject of conflicting rival claims. Since 1883 the chief progress made has been in details of design and mechanical construction. Large multipolar machines for continuous currents have been designed by Siemens and Halske, by C. E. L. Brown, and others, and are in successful operation. Disk dynamos have also been introduced by Desroziers and by Fritsche. Large alternating machines have been constructed by Ganz, by Ferranti, and by Mordey; the latter's machine having a notable improvement in the use of a single compact magnetic circuit for the field-magnet. The latest novelty is the multiphase alternate-current machine, of which the most important example is the type constructed by Brown for the transmission of power by three-phase currents from Lauffen to Frankfort.

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[1] *Nuovo Cimento* [3] i., 1881 [2] Specification of Patent, 2003 of 1878.

[3] Specification of Patent, 815 of 1880.

[4] Specifications of Patents, 4280 of 1876, 1614 and 2194 of 1882.

[5] Specifications of Patents, 4226 of 1878, 2402 of 1879, 1240 and 2954 of 1881 and 2052 of 1882.

[6] See Du Moncel's *Exposé des Applications*, i. p. 372.

[7] Specification of Patent, 512 of 1859.

[8] Specification of Patent, 924 of 1861.

[9] Specification of Patent, 5668 of 1881.

[10] Specifications of Patents, 5536 of 1881 and 2871 of 1882.

[11] Specifications of Patents, 332 of 1879, and 2893 of 1880.

[12] Specification of Patent, 400 of 1883.

[13] Specification of Patent, 973 of 1883.

[14] Specifications of Patents, 2618 and 4810 of 1882, and 4302 of 1884.

The other branch of the subject, that of the electric motor, goes back to the discovery by Faraday[2] in 1821 of electromagnetic rotation, and the invention, in 1823, by Barlow,[3] of his rotating wheel. The earliest electric motors in which the principle of attraction by an electromagnet was applied were those of Henry,[4] in 1831, and of Dal Negro,[5] in 1832, and these were followed in 1833 and 1834 by the motors of Ritchie[6] and of Jacobi,[7] and in 1837 by that of Davenport.[8] Many other inventors devised machines of this kind, some of the most famous being Page[9] in the United States, Davidson in Scotland, Wheatstone[10] in England, Froment[11] in France, and Pacinotti[1] in Italy. The discovery that the action of a dynamo is the simple converse of that of the motor, and that the same machine can serve either function, appears to have been made by Jacobi,[2] in 1850, though it only came into general recognition somewhat later. It was certainly known in 1852, for in the fourth edition of Davis's Magnetism, published at Boston, an apparatus, described as a "revolving electromagnet" (a slight modification of Ritchie's motor) is shown, on page 212, as a motor, and the same apparatus is again shown on page 268 as a generator, accompanied by the remark that "any of the electromagnetic instruments in which motion is produced by the mutual action between a galvanic current and a steel magnet may be made to afford a magneto-electric current by producing the motion mechanically. Walenn[3] explicitly stated the same point in 1860; and it was also stated by Pacinotti in 1864. The principle of transmitting power from one dynamo used as a generator to another used as motor is claimed for Fontaine and Gramme, as a discovery made in 1873, when such an arrangement was shown at Vienna. It has been noisily claimed, but without the shadow of reason, for Marcel Deprez[4], who did not, however, discover it until 1881. In 1882 Ayrton and Perry made the important discovery of the automatic regulation of motors, to run with constant velocity, by methods akin to, but the converse of, those adapted for making dynamos self-regulating. Since that date, the improvements made in continuous current motors, though great, have been in mechanical perfection of design and detail. The alternate-current dynamo does not make a convenient alternate-current motor, as it is not self-starting. When once started, however, it runs in absolute synchronism with the generator. Ferraris, in 1888, made the important suggestion to drive a motor by two independent alternate currents of similar period, but differing in phase, thus producing a rotating magnetic field. The same suggestion came independently from Nikola Tesla, who first put such motors into practical form. Many forms of rotary-field motors have since been devised; one of the most remarkable being that of Dolivo Dobrowolsky—the so-called *dreh-strom* motor—used in the Lauffen-Frankfort demonstration.

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[1] *La Lumiere Electrique*, December 3, 1881, and January 5, 1884.

[2] Journal of *Royal Institution*, September 1821.

[3] Barlow, *On Magnetic Attraction* (1823), 279; and *Encyclopædia Metropolitana* (1824), iv. art. *Electromagnetism*, 36.

[4] *Silliman's Journal*, xx. 340, 1831. Also Henry, *Scientific Writings* (1886), i. 54. [5] *Annali delle Scienze Lombardo-Veneto*, March 1834.

[6] *Phil. Trans.* 1833 [2], 318. [7] *L'Institut*, lxxxii. Dec. 1834.

[8] See *Annals of Electricity*, ii. 1838, *Encyclopædia Britannica* (ed. vii.), art. *Voltaic Electricity*, 687.

[9] *Silliman's Journal*, xxxiii. 1838; and [2] x. 344 and 473, 1850.

[10] Specification of Patent, 9022 of 1841.

[11] See *Cosmos*, x. 495, 1857, and *La Lumiere Electrique*, ix. 193, June 1883.

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[1] *Nuovo Cimento*, xix. 378, 1865.

[2] *Mémoire sur la Théorie des Machines électromagnétiques.*

[3] Specification of Patent, 2587 of 1860.

[4] Specification of Patent, 2830 of 1882. See *Journ. Soc. Telegr. Engineers*, xii. 301, 1883.

The theory of the dynamo dates back to the investigations of Weber[1] and of Neumann[2] respecting the general laws of magneto-electric induction, followed by Jacobi's[3] calculations and experiments respecting the performance of an electric motor, by Poggendorff's[4] and Koosen's[5] investigations of the theory of the Saxton magneto-machine, and by the researches of Lenz,[6] Joule,[7] Le Roux,[8] and of Sinsteden.[9] These researches were followed at a long interval by those of Favre,[10] followed by silence for twenty years, broken only by the pregnant, but almost totally forgotten, little paper in which Clerk-Maxwell[11] laid down a theory for self-exciting machines. On the revival of electric lighting the theory of the dynamo was again studied, important contributions being made by Mascart,[12] Hagenbach,[13] von Waltenhofen,[14] Hopkinson,[15] Herwig,[16] Meyer and Auerbach,[17] and Joubert.[18] The latter founded the modern theory of alternate-current machines. Hopkinson[19] devised the method of representing, by a curve, the relation between the current and the working electromotive force of the machine; such curves, under the name of "characteristics," subsequently formed the basis of the theoretical researches of Marcel Deprez.[20] In 1880 Frölich[21] began a series of investigations both experimental and theoretical, that led to equations of remarkable simplicity, if not of more than approximate value, and in 1883 Clausius,[22] adopting Frölich's fundamental expression for the law of the electromagnet, evolved with great elaboration a theory in which all the various secondary effects arising in generators were taken into account—a theory which he later extended to the case of motors. In 1886 John and Edward Hopkinson[1] published a remarkable paper, developing, from theoretical considerations respecting the induction of magnetism in a magnetic circuit of given form and materials, a theory of the dynamo, the perfection of which may be judged by the fact that its use, as now extended by various workers, enables the performance of a machine to be predicted with extraordinary accuracy from the design as laid down in the working drawings. Other contributions to the theory of dynamos have been made by Sir W. Thomson[2] (windings to secure maximum efficiency), Kapp[3] (pre-determination of characteristic curve), Rücker[4] (limits of self-regulation), Esson,[5] (design of multipolar machines), and others. Hering,[6] Fritsche,[7] and Arnold[8] have published studies on the modes of winding armatures; and the latter has given a formula for all kinds of continuous-current machines with closed-coil armatures. Methods of analyzing the various losses of energy due to friction, hysteresis, and eddy-currents have been devised by Mordey,[9] and later by Kapp[10] and Housman,[11] independently.

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[1] *Elektrodynamische Maasbestimmungen* (1846).

[2] *Berliner Berichte*, p. 1, 1845; and p. 1, 1847.

[3] *Pogg. Ann.*, li. 370, 1840; lxix. 181, 1846; and *Krönig's Journal*, iii. 377, 1851. Also *Ann. Chim. Phys.* [3] xxxiv. 451, 1852.

[4] *Pogg. Ann.*, xlv. 390, 1838.

[5] *Pogg. Ann.*, lxxxv. 226; and lxxxvii. 386, 1852.

[6] *Pogg. Ann.*, xxxi. 483, 1834; xxxiv. 385, 1835; and xcii. 128, 1854.

[7] *Annals of Electricity*, iv. v. 1839–40; *Phil. Mag.* [3] xxiii. 263, 347, and 435, 1843.

[8] *Ann. Chim. Phys.* [3] l. 463, 1857.

[9] *Pogg. Ann.*, lxxxiv. 181, 1851.

[10] *Comptes Rendus*, xxxiv. 342, 1853; xxxix. 1212, 1854; xlvi. 337, 658, 1858.

[11] *Proc. Roy. Soc.*, Mar. 14, 1867; and *Phil. Mag.* [4] xxxiii. [474], 1867.

[12] *Journal de Physique*, vi. 204, 297, 1877; and vii. 89, 1878.

[13] *Archives des Science Physiques*, lv. 255, March, 1876; and *Pogg. Ann.*, clviii. 599, 1876.

[14] *Wiener Berichte*, lxxx. 601, 1879.

[15] *Proc. Inst. Mech. Engineers*, 238, 1879, and 266, 1880.

[16] *Wied. Ann.*, viii. 494, 1880.

[17] *Wied. Ann.*, viii. 494, 1879.

[18] *Ann. de l' Ecole Normale*, x. 131, 1881; and *Journal de Physique* [2] ii. 293, 1883.

[19] *Proc. Inst. Mech. Engineers*, 238, 1879.

[20] *Comptes Rendus*, xcii. 1152, 1881; and *La Lumière Electrique*, xv. 1, 1885.

[21] *Berl. Berichte*, 962, 1880; *Electrotechnische Zeitschrift*, ii. 134, 170, 1881; vi. 128, etc., 1885; and ix., Nov., 1888.

[22] *Wied. Ann.*, xx. 353, 1883; xxi. 385, 1884; *Phil. Mag.* (5) xvii. 49 and 119, 1884.

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[1] *Phil. Trans.*, i. 331, 1886.
[2] *Journal de Physique* (2) ii. 240, 1887; and *Comptes Rendus*, xciii. 474, 1881.
[3] *Journ. Soc. Telegr. Engineers*, xv. 518, 1887.
[4] *Phil. Mag.* (5) xix., 462, June, 1885.
[5] *Journal Inst. Electrical Engineers*, xx. 1891.
[6] Hering's *Principles of Dynamo-Electric Machines*, New York, 1889.
[7] Fritsche's *Die Gleichstrom-Dynamomaschine*, Berlin, 1889.
[8] Arnold's *Die-Ankerwickelung der Gleichstrom-Dynamomaschinen*, Berlin, 1891.
[9] *Journal Inst. Electrical Engineers*, xviii. 620, 1889.
[10] *Electrician*, xxvi. 700, 1891.
[11] *Ib.*; see also *Journal Inst. Electrical Engineers*, xx. 303, 1891.

CHAPTER III.

PHYSICAL THEORY OF DYNAMO-ELECTRIC MACHINES.

ALL dynamos are based upon the discovery made by Faraday in 1831, that electric currents are generated in conductors by moving them in a magnetic field. Faraday's principle may be enunciated as follows:—When a conductor is moved in a field of magnetic force in any way so as to cut the lines of force, there is an electromotive-force produced in the conductor, in a direction at right angles to the direction of the motion, and at right angles also to the direction of the lines of force, and to the right of the lines of force, as viewed from the point from which the motion originates.[1]

Dr. Fleming has given a most useful rule for remembering this connexion between motion, magnetism, and induced current. Hold the thumb and the first and middle fingers of the right hand as nearly as possible at right angles to each other, as in Fig. 9, so as to represent three rectangular axes in space. If the thumb point in the direction of the motion, and the forefinger point along the direction of the magnetic lines, then the middle finger will point in the direction of the induced electromotive-force.

This induced electromotive-force is, as Faraday showed, proportional to the number of lines of magnetic force[2] cut per second; and is, therefore, proportional to the intensity of the Magnetic "field," and to the length and velocity of the moving conductor. For steady currents, the flow of electricity in the conductor is, by Ohm's well-known law, directly proportional to this electromotive-force, and inversely proportional to the resistance of the conductor. For sudden currents, or currents whose strength is varying rapidly, this is no longer true. And it is one of the most important matters, though one too often overlooked in the construction of dynamo-electric machinery, that the "resistance" of a coil of wire, or of a circuit, is by no means the only obstacle offered to the generation of a momentary current in that coil or circuit; but that, on the contrary, the "self-induc-

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[1] A more usual rule for remembering the direction of the induced currents is the following adaptation from Ampère's well-known rule:—Supposing a figure swimming in any conductor to turn so as to look along the (positive direction of the) lines of force. Then, if he and the conductor be moved towards his right hand, he will be swimming with the current induced by this motion.

[2] For the numerical signification to be attached to the term "number of magnetic lines," see p. 123.

Fig. 9.

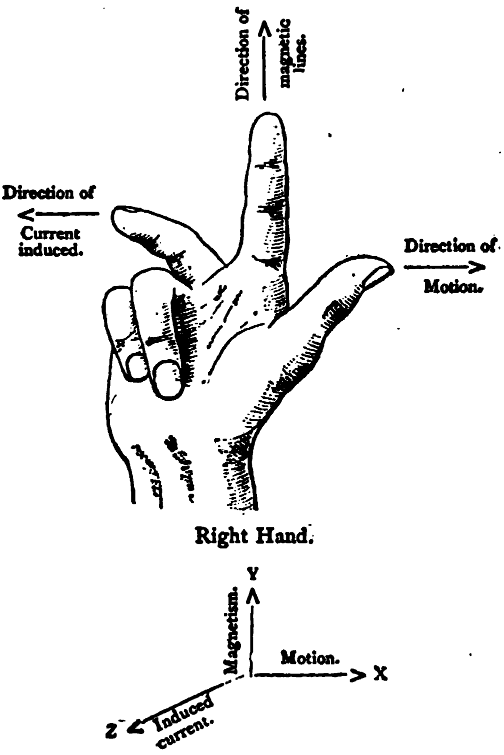


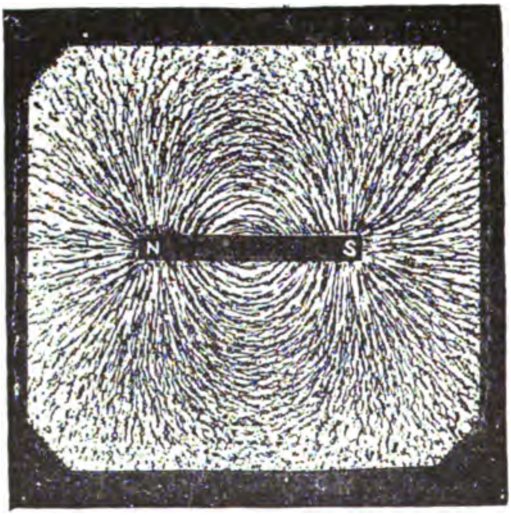
Illustration of Fleming's Rule.

tion " exercised by one part of a coil or circuit upon another part or parts of the same, is a consideration, in many cases quite as important as, and in some cases more important than, the resistance.

To understand clearly Faraday's principle—that is to say, how it is that the act of moving a wire so as to cut magnetic lines of force can generate a current of electricity in that wire—let us inquire what a current of electricity is.

A wire through which a current of electricity is flowing looks in no way different from any other wire. No man has ever yet seen the electricity running along in a wire, or knows precisely what is happening there. Indeed, it is still a disputed point which way the electricity flows, or whether or not there are two currents flowing simultaneously in opposite directions. One thing is certain; that the energy does not flow along the substance of the wire at all, but is transmitted across the surrounding medium, transversely. Until we know with absolute certainty what electricity is, we cannot expect to know precisely what a current of electricity is.

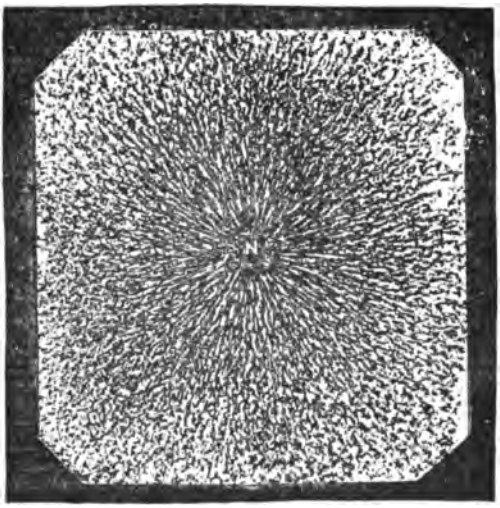
FIG. 10.



MAGNETIC FIELD OF BAR-MAGNET.

But no electrician is in any doubt as to one most vital matter, namely, that when that which is called an electric current flows through a wire, the magnetic forces with which that wire is thereby, for the time, endowed, resides not in the wire at all, but in the space surrounding it. Every one knows that the space or "field" surrounding a magnet is full of magnetic "lines of force," and that these lines run in tufts from the N-pointing pole to the S-pointing pole of the magnet, invisible until, by dusting iron filings into the field, their presence is made known, though they are always in reality there (Fig. 10). A view of the magnetic field at the pole of a bar magnet, as seen end-on, would, of course, exhibit merely radial lines, as seen in Fig. 11.

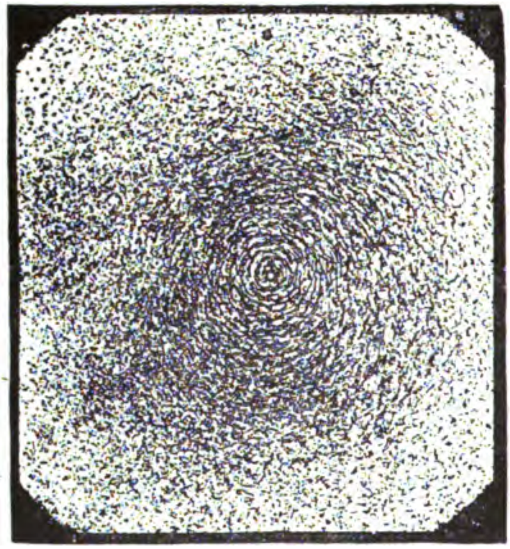
FIG. 11.



MAGNETIC FIELD ROUND ONE POLE, END-ON.

Now, every electric current (so-called) is surrounded by a magnetic field, the lines of which can be similarly revealed. To observe them, a hole is bored through a card or a piece of glass, and the wire which carries the current must be passed up through the hole. When iron filings are dusted into the field they assume the form of concentric circles (Fig. 12), showing that the lines of force run completely round the wire, and do not stand out in tufts. In fact, every conducting wire is surrounded by a sort of magnetic whirl, like that shown in Fig. 13. A great part of the energy of the so-called electric current in the wire consists in these external magnetic whirls. To set them up requires an expenditure of energy; and to maintain them requires also a constant expenditure of energy. It is these magnetic whirls which act on magnets, and cause them to set, as galvanometer needles do, at right angles to the conducting wire.

FIG. 12.

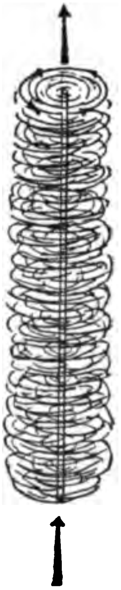


MAGNETIC FIELD SURROUNDING CURRENT. THE CONDUCTING WIRE SEEN END-ON.

Now, Faraday's principle is nothing more or less than this:—That by moving a wire near a magnet, across a space in which there are magnetic lines, the motion of the wire, as it cuts across those magnetic lines, sets up magnetic whirls round the moving wire, or, in other language, generates a so-called current of electricity in that wire. Poking a magnet pole into a loop or circuit of wire also necessarily generates a momentary current in the wire loop, becauses it momentarily sets up magnetic whirls. In Faraday's language, this action increases the number of magnetic lines intercepted by the circuit.

It is, however, necessary that the moving conductor should, in its motion, so cut the magnetic lines as to alter the number of lines of force that pass through the circuit of which the moving conductor forms part. If a conducting circuit—a wire ring or single coil, for example—be moved along in a uniform magnetic field, as indicated in Fig. 14, so that only the same lines of force pass through it, no current will be generated. Or if, again, as in Fig. 15, the coil be moved by a motion of translation to another part of the uniform field, as many lines of force will be left behind as are gained in advancing from its first to its second position, and there will be no current generated in the coil. If the coil be merely rotated on itself round a central axis, like the rim of a fly-wheel, it will not cut any more lines of force than before, and this motion will generate no current. But if, as in Fig. 16, the coil be tilted in its motion across the uniform field, or rotated round any axis in its own plane, then the number of lines of force that traverse it will be altered, and currents will be generated. These currents will flow round the ring coil in the right-handed direction (as viewed by a person looking along the magnetic field in the direction in which the magnetic lines run, if the effect of the movement is to diminish the number of lines of force that cross the coil; they will flow round in the opposite sense, if the effect of the movement is to increase the number of intercepted lines of force.

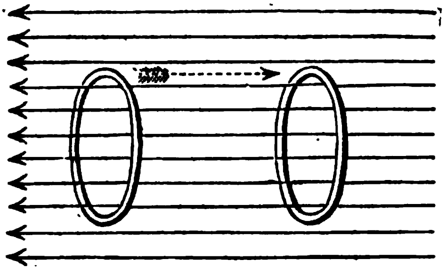
FIG. 18.



MAGNETIC WHIRL SURROUNDING WIRE CARRYING CURRENT.

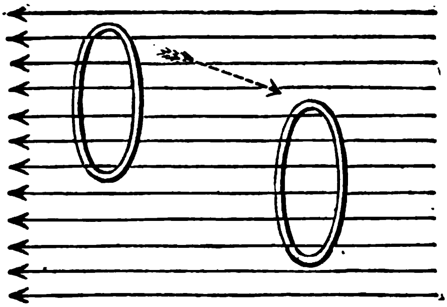
If the field of force be not a uniform one, then the effect of taking the coil by a simple motion of translation from a place where the lines of force are dense to a place where they are less dense, as from position 1 to position 2 in Fig. 17, will be to generate currents. Or, if the motion be to a place where the lines of force run in the reverse direction,[1] the effect will be the same, but even more powerful.

FIG. 14.



CIRCUIT MOVED WITHOUT CUTTING LINES OF FORCE OF UNIFORM MAGNETIC FIELD.

FIG. 15.



CIRCUIT MOVED WITHOUT CUTTING ANY MORE LINES OF FORCE.

We may now summarize the points under consideration and some of their immediate consequences, in the following manner:—

(1) A part, at least, of the energy of an electric current

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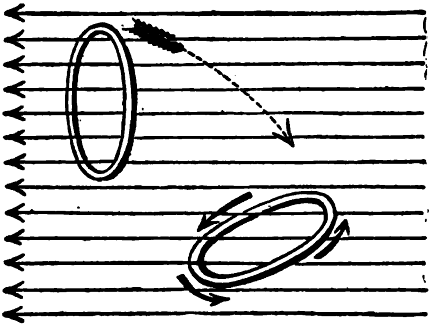
[1] As a matter of fact, it would be impossible to have a magnetic field exactly like Fig. 17; for in the intermediate part, between the upper and lower fields, the magnetic lines would be of curved complex form.

exists in the form of magnetic whirls in the space surrounding the conductor.

(2) Currents can be generated in conductors by setting up magnetic whirls round them.

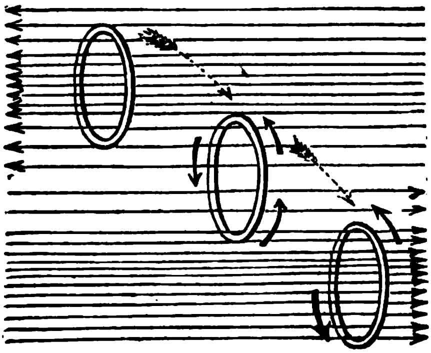
FIG. 16.



CIRCUIT MOVED SO AS TO ALTER NUMBER OF LINES OF FORCE THROUGH IT.

(3) We can set up magnetic whirls in conductors by moving magnets near them, or moving them near magnets.

FIG. 17.



MOTION OF CIRCUIT IN NON-UNIFORM MAGNETIC FIELD.

(4) To set up such magnetic whirls, and to maintain them by means of an electric current circulating in a coil,

requires a continuous expenditure of energy, or, in other words, consumes power.

(5) To induce currents in a conductor, there must be relative motion between conductor and magnet, of such a kind as to alter the number of lines of force embraced in the circuit.

(6) Increase in the number of lines of force embraced by the circuit produces a current in the opposite sense to decrease.

(7) Approach induces an electromotive-force in the opposite direction to that induced by recession.

(8) The more powerful the magnet-pole or magnetic field the higher will be the electromotive-force generated.

(9) The more rapid the motion, the higher will be the electromotive-force.

(10) By joining in series a number of such moving conductors, the electromotive-forces in the separate parts are added together; hence very high electromotive-forces can be obtained by using numerous coils properly connected.

(11) Since the quantity or strength of the current depends on the resistance of the conductors in the circuit, as well as on the electromotive-force, all unnecessary resistance should be avoided.

(12) Approach being a finite process, the method of approach and recession (of a coil towards and from a magnet pole) must necessarily yield currents alternating in direction.

(13) By using a suitable commutator, all the currents, direct or inverse, produced during recession or approach, can be turned into the same direction in the wire that goes to supply currents to the external circuits; and if the rotating coils are properly grouped so that before the electromotive-force in one set has died down another set is coming into action, then it will be possible, by using an appropriate commutator, to combine their separate currents into one practically uniform current.

(14) To the moving conductor which is generating the electromotive-force by cutting the magnetic lines, it makes no difference what the origin of those lines is, whether from

a permanent magnet of steel or from an electromagnet, provided the number of magnetic lines so cut is the same.

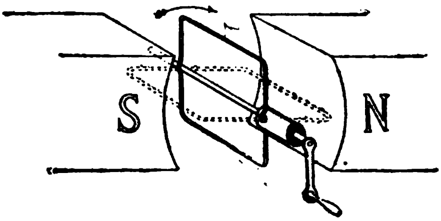
(15) To the moving conductor it makes no difference what the origin of the motion is. Whether the motion be due to a steam-engine, or to a gas-engine, or to hand-driving, or to the driving of an electric current in the wire itself (as in the case of electric motors), it makes no difference to the moving conductor, which, provided the speed and the number of magnetic lines to be cut are given, will generate the same electromotive-force.

To make more clear the considerations which will occupy us when discussing individual types of dynamo, we will first examine some fundamental points in the general mechanism and design of dynamo machines; for there are many additional conditions to be observed in the construction of a successful dynamo. We will deal with the various matters in order, beginning with the various organs or part of the machine. Having discussed these, we take up the nature of the processes that go on in the machine when it is at work, the action of the magnetic field on the rotating armature, the reactions of the armature upon the field in which it rotates. We must then enter upon the magnetic part of the subject, and discuss the magnetic properties of iron so far as is needed for the purpose of dynamo design. We shall then consider the design of field-magnets, and the design and construction of armatures.

ORGANS OF DYNAMO-ELECTRIC MACHINES.

The simplest conceivable dynamo is that sketched in Fig. 18, consisting of a single rectangular loop of wire rotating in a simple and uniform magnetic field between the poles of a large magnet. If the loop be placed at first in the vertical plane, the number of lines that pass through it from right to left will be a maximum, and as it is turned into the horizontal position the number diminishes to zero; but on continuing the rotation the lines begin again to thread through the loop from the opposite side, so that there is a negative maximum when the loop has been turned through 180°. During the half-revolution, therefore, currents will have been induced in the loop, and these currents will be in the direction from back to front in the part of the loop which is rising on the left, and in the opposite direction, namely from front to back, in that part which is descending on the right. On passing the 180° position, there will begin an induction in the reverse sense, for now the number of negative lines of force is diminishing, which is equivalent to a positive increase in the number of lines of force : and this increase would go on until the loop reached its original position, having made one complete turn. If, then, to each end of the loop there were separately attached a metal collar on the shaft, and on each collar there pressed a spring, wires connected to these springs would convey an *alternating current* to the circuit. If, however, it is desired to adapt the apparatus to furnish a continuous current, a special adjunct must be added.

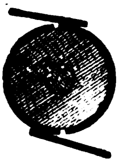
Fig. 18.



Ideal Simple Dynamo.

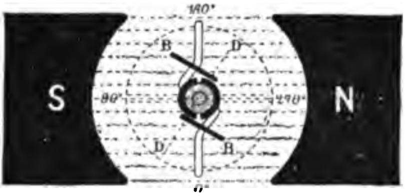
To commute these alternately-directed currents into one direction in the external circuit, there must be applied a commutator consisting of a metal tube slit into two parts, and mounted on a cylinder of hard wood or other suitable insulating material ; each half being connected to one end of the loop, as indicated in Fig. 18. Against this commutator press a couple of metallic springs or "brushes" (Fig. 19), which lead away the currents to the main circuit. It is obvious that if the brushes are so set that the one part of the split tube slides out of contact, and the other part slides into contact with the brush, at the moment when the loop passes through the positions when the induction reverses itself, the alternate currents induced in the loop will be "commuted" into one direction through the circuit. We should expect therefore the brushes to be set so that the commutation shall take place exactly as the loop passes through the vertical position. In practice, however, it is found that a slight forward lead must be given to the brushes, for reasons which will presently appear. In Fig. 20 are shown the brushes B B′, displaced so as to touch the commutator not exactly at the highest and lowest points, but at points displaced in the direction of the line D D, which is called the "diameter of commutation." The argument is in no wise changed if for the single ideal loop we substitute, as proposed by Sturgeon in 1835, the simple rectangular coil represented in Fig. 21, consisting of many turns of wire, in each of which a simultaneous inductive action is going on, making the total induced electromotive-force proportionally greater. This form, with the addition of an iron core is, indeed, the form given to armatures in 1856 by Siemens, whose shuttle-wound armature is represented in section in Fig. 22. A small magneto-electric machine of the old pattern, having the shuttle-wound armature, is shown in

Fig. 19.



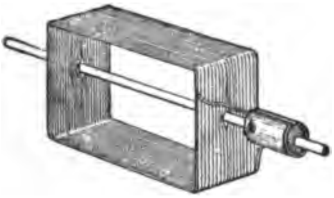
Two-part Commutator.

Fig. 20.



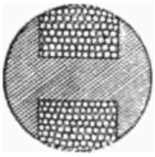
Simple Loop in Simple Field.

Fig. 21.



Simple Rectangular Coil.

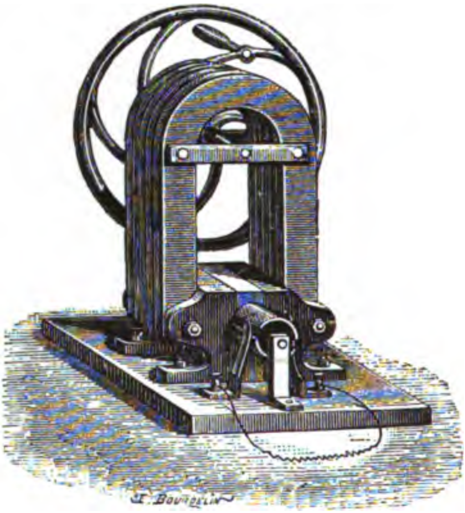
Fig. 22.



Section of old Shuttle-wound Siemens Armature.

Fig. 23. Though this form has now for many years been abandoned, save for small motors and similar work, it gave a great impetus to the machines of its day; but for all large work it has been entirely superseded by the ring armatures and drum armatures presently to be described.

Fig 23.



Old Siemens Machine, with Shuttle-wound Armature and Permanent Magnets.

Essential Parts of a Dynamo.

We have seen that the dynamo in its simplest form consists of two main portions: (1) an *armature*, which in revolving induces electromotive-forces in the copper conductor wound upon it; (2) a *field-magnet*, that is to say a magnet whose function is to provide a field of magnetic lines, to be cut by the armature conductors as they revolve. In all dynamos, whether for continuous currents or for alternate currents, these two parts can be recognized. In almost all continuous-current machines the field-magnet stands still, and consists of a comparatively simple and massive electromagnet; whilst the armature, which is a more complex structure, is the portion which rotates. In alternate-current machines the field-magnet is usually multipolar, and in the majority of cases is stationary, whilst the armature rotates; nevertheless there are many alternators of recent pattern in which the armature stands still and the field-magnet rotates. The criterion as to which portion is properly called "field magnet," and which "armature," is not the question of rotation or otherwise. The name of field-magnet is properly given to that part which, whether stationary or revolving, maintains its magnetism steady during the revolution; and the name armature is properly given to that part which, whether revolving or fixed, has its magnetism changed in a regularly repeated fashion when the machine is in motion.

In the case of continuous-current machines there is another feature of first importance, namely, the apparatus for collecting the currents from the revolving armature. This apparatus consists of two essential parts; the *commutator* (or *collector*) attached to the armature and revolving with it, and the *brushes*. The latter, which are conducting contact pieces held pressed against the surface of the rotating commutator, are provided with special *brush-holders* mounted upon an adjustable frame or *rocker*.

In the case of alternate-current machines there is no need of a commutator; but, in general, these machines have to be provided with some device for making a sliding connexion. For in those forms in which the armature rotates, its coils must be brought into continuous metallic relation with the conductors of the main circuit; and in those forms in which the armature is stationary and no such arrangement is needed at that part, there must still be sliding contacts to maintain the coils of the revolving field-magnet part in continuous metallic connexion with the auxiliary exciting circuit. In either case the appropriate device consists of a pair of *collecting rings*, against each of which a *brush* presses.

In addition to the electrical and magnetic features enumerated above, there are certain purely mechanical features which need to be considered. The revolving part must be mounted on an appropriate *spindle* or *shaft*, the design of which is a matter of mechanical engineering. To transmit the power from the spindle to the revolving conductors of the armature there are required *driving attachments* properly secured to the spindle. The spindle itself must be supported in suitable *bearings*, and be provided with *lubricators* to secure cool running. To receive the power from the engine a *pulley* must be provided, unless the dynamo is to be driven direct by a *coupling* from an engine mounted on the same bed-plate. Lastly, the whole dynamo must be erected upon an appropriate *bed-plate*, which in some cases is placed upon *rails*, so that it may be shifted from time to time by the aid of tightening screws, as the belt grows slack.

In the considerations which follow, attention will be concentrated upon dynamos for producing continuous currents, the various organs of which will be duly considered. The design of alternate-current machines will be discussed in a later chapter.

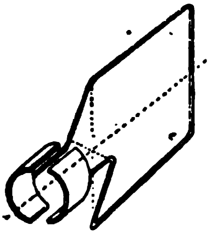
CONTINUOUS-CURRENT DYNAMOS.

Armatures.

Returning to the ideal simple loop, we may exhibit it in its relation to the 2-part commutator somewhat more clearly by referring to Fig. 24. The same split-tube or 2-part commutator will suffice if a loop of two or more turns be substituted, as shown in Fig. 25, for the single turn.

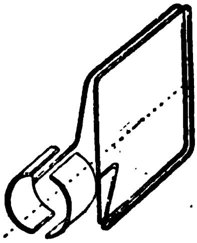
But we may substitute also for the one loop a small coil consisting of several turns wound upon an iron ring. This coil (Fig. 26), which may be considered as one section of a Pacinotti or Gramme ring, will have lines of force induced through it as the loop had. In the position drawn, it occupies the highest point of its path, and the induction of lines of force through it will be a maximum. As it turns, the number of lines of force threaded through it will diminish, and become zero when it is at 90° from its original position. But a little consideration of its action will suffice to show that if another coil be placed at the opposite side of the ring it will be undergoing exactly similar inductive action at the same moment and may therefore be connected to the same commutator. If these two coils are united in parallel arc, as shown in Fig. 27, the joint electromotive-force will be the same as that due to either separately; but the resistance offered to the current by the two jointly is half that of either.

FIG. 24.



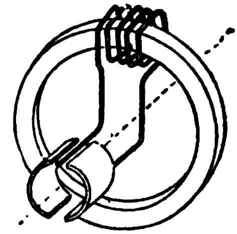
SIMPLE LOOP ARMATURE.

FIG. 25.



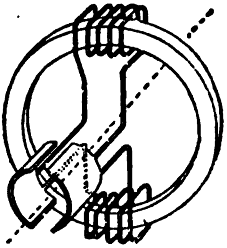
LOOP ARMATURE OF TWO TURNS.

FIG. 26.



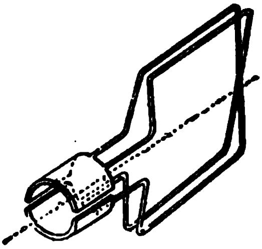
SIMPLE RING ARMATURE WITH ONE COIL.

FIG. 27.



SIMPLE RING ARMATURE WITH TWO COILS IN PARALLEL.

FIG. 28.

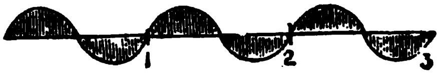


SIMPLE LOOP ARMATURE WITH TWO COILS IN PARALLEL.

It is evident that we may connect two parallel loops in a similar fashion to one simple 2-part collector. If the two loops are of one turn each, we shall have the arrangement sketched in Fig. 28; but the method of connecting is equally good for loops consisting of many turns each.

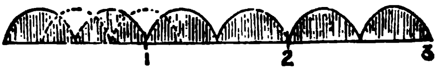
Now, with all these arrangements involving the use of a 2-part commutator, whether there be one circuit only or two circuits in parallel in the coils attached thereto, there is the disadvantage that the currents, though commutated into one direction, are not absolutely continuous. In any single coil without a commutator there would be generated, in successive revolutions, currents whose variations might, if the coil were destitute of self-induction, be graphically expressed by a recurring sinusoidal curve, such as Fig. 29. But if by the addition of a simple split-tube commutator the alternate halves of these currents are reversed, so as to rectify their direction through the rest of the circuit, the resultant currents will not be continuous, but will be of one sign only, as shown in Fig. 30, there being two currents generated during each revolution of the coil. The currents are now "rectified," or "redressed," as our continental neighbours say, but are not continuous. To give *continuity* to the currents, we must advance from the simple 2-part commutator to a form having a larger number of parts, and employ therewith a larger number of coils. The coils must also be so arranged that one set comes into action while the other is going out of action. Accordingly, if we fix upon our iron ring two sets of coils at right angles to each other's planes, as in Fig. 31, so that one comes into the position of best action while the other is in the position of least action (one being parallel to the lines of force when the other is normal to them), and their actions be superposed, the result will be, as shown in Fig 32, to give a

FIG. 29.



SIMPLE CURVE OF SINES, REPRESENTING AN ALTERNATING OR UNDULATORY CURRENT.

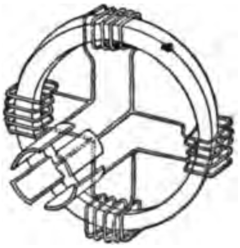
FIG. 30.



CURVE OF RECTIFIED OR COMMUTED ALTERNATING CURRENT.

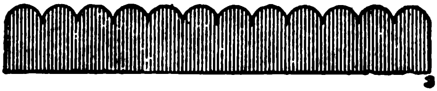
current which is continuous, but not steady, having four slight undulations per revolution. If any larger number of separate coils are used, and their effects, occurring at regular intervals, be superposed, a similar curve will be obtained, but with summits proportionately more numerous and less elevated. When the number of coils used is very great, and the overlappings of the curves are still more complete, the row of summits will form practically a straight line, or the whole current will be practically constant. As arranged in Fig. 31, the four coils are all united together in a *closed* circuit, the end of the first being united to the beginning of the second, and so forth all round, the last section closing in to the first. For perfect uniformity of effect, the coils on the armature ought to be divided into a very large number of sections (see calculations p. 221, Chap. IX.), which come in regular succession into the position of maximum induction at regular intervals one after the other. In Fig. 33 a sketch is given of a drum armature wound with two pairs of coils at right angles one to the other, and connected to a 4-part commutator. A little examination of Figs. 31 and 33 will show that each section of the coils is connected to the next in order to it; the whole of the windings constituting, therefore, a single closed coil. Also, the end of one section and the beginning of the next are both connected with a segment of the commutator. In practice, the commutator segments are not mere slices of metal tubing, but are built up of a number

Fig. 31.



Four part Ring Armature (Closed Coil.)

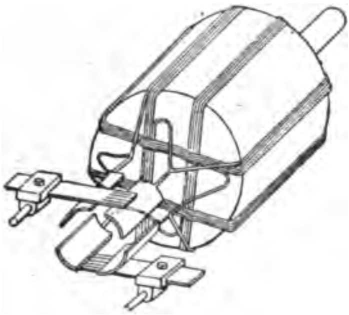
Fig. 32.



Curve of Continuous but Non-uniform Current.

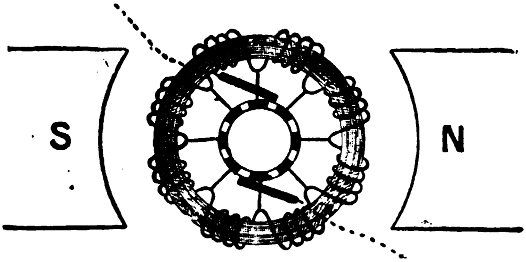
of parallel bars of copper, gun-metal, or phosphor-bronze, such as may be seen in Fig. 36, p. 43, placed round the periphery of a cylinder of some insulating substance. It will also be noticed that, owing to the fact that there is a continuous circuit all round, there are two ways in which the current may flow through the armature from one brush to the other, as in all the ring and drum armatures; of which, indeed, Figs. 31 and 33 may be taken as simplified instances. The same reasoning now applied to 4-part armatures holds good for those having a still larger number of parts, such as is shown in Fig. 34. Of these more will be said in the subsequent chapters. Let it suffice to say here that in closed-coil armatures, whether of the "ring" or the "drum" type, there are usually as many segments to the commutator as there are *sections* or groups of coils in the circuit of the armature. The special case of *open-coil armatures* is considered in Chapter XVII., p. 449. In these machines the separate coils are not connected up together in series, and a special form of commutator is used instead of the usual arrangement of a large number of parallel bars.

FIG. 33.



FOUR-PART DRUM ARMATURE (CLOSED COIL).

FIG. 34.



SIMPLE RING ARMATURE, SHOWING CONNEXIONS OF CLOSED COIL.

As already explained, the "brushes" press against the commutator, being usually held in position by a spring. As the commutator rotates, each of the bars passes successively under the brush, and makes contact with it. At one side—that towards which the two currents in the armature are flowing—the current flows from the commutator-bar into the brush. At the other side the return current flows from the negative brush into the commutator-bar in contact with it, and thence divides into two parts in the two circuits of the armature. Since the brushes press against the commutator-bars, then when one commutator-bar is leaving and the next coming up into contact with the brush, there will be contact made for a moment with two adjacent bars; and the coil, or section, whose two ends are united to these two bars, will, for an instant, be short-circuited. The effect of this will be considered in dealing with the reactions in armatures at a later stage.

So far, the only types of armature considered have been the "drum" type, and the "ring" type; but these are not the only possible cases. The object of all such combinations of coils is to obtain the practical continuity and equability of current explained above. To attain this end it is needful that some of the individual coils should be moving through the position of maximum action, whilst others are passing through the neutral point, and are temporarily idle. Hence, a symmetrical arrangement of the individual coils or groups of coils around an axis is needed; and such symmetrical arrangements may take one of the four following types :—

(1) *Ring armatures*, in which the coils are grouped upon a ring whose principal axis of symmetry is its axis of rotation also.

(2) *Drum armatures*, in which the coils are wound longitudinally over the surface of a drum or cylinder.

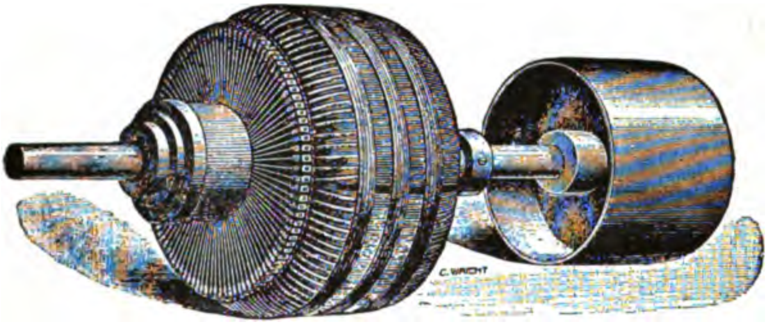
(3) *Pole armatures*, having coils wound on separate poles projecting radially all round the periphery of a disk or central hub.

(4) *Disk armatures*, in which the coils are flattened against a disk.

Ring armatures are found in many machines, but the ingenuity of inventors has been exercised chiefly in three directions:—The securing of practical continuity, the avoidance of eddy-currents in the cores, and the reduction of useless resistance. In the greater part of these machines the armatures are constructed with closed coils; but there is no reason why open-coil armatures should not be constructed in the ring form, as indeed is the case with the well-known Brush arc-light dynamo. Most inventors have been content to secure approximate continuity by making the number of sections numerous. Pacinotti's early dynamo had the coils wound between projecting teeth upon an iron ring. Gramme rejected these cogs, preferring that the coils should be wound around the entire surface of the endless core. To prevent wasteful currents in the cores, Gramme employed for that portion a coil of varnished iron wire of many turns. For cylindrical armatures flat core-disks of sheet iron are now almost universally preferred. For discoidal ring armatures the core is built of hoops. The parts of the copper coils which pass through the interior of the ring are inoperative in cutting magnetic lines, unless there are pole-pieces of the field-magnet projecting internally. Hence, in the ordinary forms of dynamo with exterior magnets, the inner parts of the ring winding act merely as conductors and not as inductors, and offer a certain amount of wasteful resistance. But this resistance in well-designed machines is insignificant compared with that of the external circuit, and the disadvantage is largely imaginary. Inventors have essayed to reduce the amount of copper, by either fitting projecting flanges to the pole-pieces, or by using internal magnets, or else by flattening the ring into a disk form, so as to reduce the interior parts of the ring coils into an insignificant amount. Indeed, the flat-ring armatures may be said to present a distinct type from those in which the ring tends to the cylindrical form. In some large recent German dynamos the ring is outside the field-magnets, so that the outer part of the windings are non-inductive or idle; and the currents are collected direct from the ring by brushes which trail on its periphery.

The various modes of winding and connecting up the conductors on an armature are specially considered in Chapter XII. A finished ring armature with its commutator and driving pulley is shown in Fig. 35.

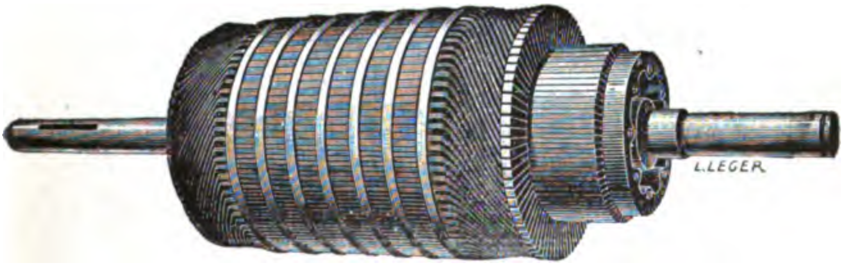
Fig. 35.



Ring Armature of Gramme Dynamo (Fuller's Pattern).

Drum armatures, as first constructed by Siemens, had iron cores made of wire wound upon an internal non-magnetic nucleus. Weston substituted stamped core-disks of iron with teeth. Edison, iron core-disks without teeth. Special modes of winding or joining the copper conductors have been devised by many inventors. A complete drum armature is depicted in Fig. 36, which shows the overlapping of the windings at the end of the drum, the connexions to the commutator, and the external binding wires that keep the coils from flying out.

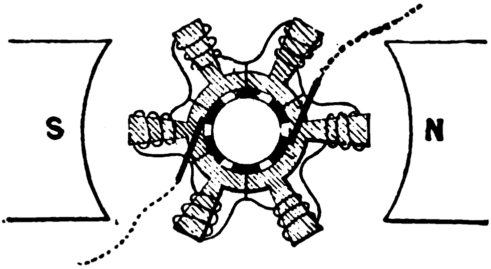
Fig. 36.



Drum Armature (Allgemeine Co.'s Pattern).

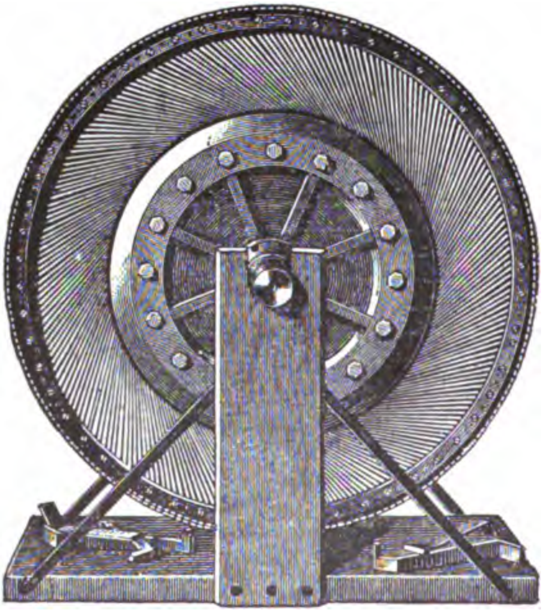
Pole armatures, having the coils wound upon radially projecting poles have been devised by Allan, Lontin, and Weston. The principle of Lontin's machine, in which the coils are connected like the sections of a Pacinotti or Gramme ring, is indicated in Fig. 37. Here the diameter of commutation is parallel to the polar diameter, because the number

FIG. 37.



SIMPLE POLE ARMATURE SHOWING CONNEXIONS.

FIG. 38.



DISK ARMATURE OF FRITSCHE MACHINE.

of lines of force in this case is a maximum in the coils that are on the right and left positions. This armature is structurally a difficult one, because it is not mechanically strong unless the cores are solid; and solid cores are electrically bad owing to their heating. It is impracticable, too, in this form to have very many sections, and the coils act, by reason of their position, prejudicially on one another. This form of armature is obsolete for direct-current machines.

Disk armatures are now differentiated into two kinds: (1) those in which the coils are grouped on a number of small bobbins, side by side, an arrangement suitable for alternate current machines, such as those of Wilde, Siemens, Ferranti, and Mordey; (2) those in which the windings are made to overlap over a considerable angle of the periphery, as in the disk dynamos of Pacinotti, of Rupp and Jehl, of Desroziers, and of Fritsche, all of which are adapted to give continuous currents. It is usual, in the disk form of armature, to dispense with any iron core, for, the armature being thin, can be inserted in a comparatively narrow gap between the polar surfaces of the field-magnet. A finished disk armature is shown in Fig. 38, belonging to a Fritsche machine; the commutator being on the outside of the disk.

Armature Cores.

Whenever iron is employed in armatures, it must be slit or laminated, so as to prevent the generation of eddy-currents. Such iron cores should be structurally divided in planes normal to the circuits round which electromotive-force is induced; or should be divided in planes parallel to the lines of force and to the direction of the motion. Thus, drum armature cores should be built of disks of thin sheet iron. Ring armatures, if of the cylindrical or elongated type, should have cores made up of rings stamped out of sheet iron and clamped together side by side; but if of the flat ring type they should be built of concentric hoops. Cores built up of varnished iron wire, or of thin disks of sheet iron separated by varnish, asbestos paper, or mica, partially realize the required condition. The magnetic discontinuity of wire cores is, however, to a certain extent disadvantageous; it is better that the iron should be without discontinuity in the direction in which it is to be magnetized. It should, therefore, be laminated into sheets, rather than subdivided into wires. Pole armatures are structurally unsatisfactory unless the projections which receive the coils are very short. Cores of solid iron are quite inadmissible, as currents are generated in them and heat them. Cores of solid metal other than iron—for example, of gun-metal, or of phosphor-bronze—should on no account be used in any armature; but the driving supports are necessarily strong and solidly made.

Fundamental Points in Design.

As has already been pointed out, the function of the field-magnet is to provide a large number of magnetic lines, whilst the function of the armature is to cut the magnetic lines so provided. The iron core inside the armature may be regarded, therefore, as belonging to the magnetic circuit of the field-magnet; the true armature consisting of the rotating copper conductors. There is no electrical necessity for the iron core inside the armature to rotate; indeed, in some ways it would act more efficiently if it did not. But purely mechanical considerations require that in both ring armatures and drum armatures the core should rotate with the coils. In all dynamos the electromotive-force is proportional at every instant to the rate at which the magnetic lines are being cut, and this will again be proportional to three quantities: (1) the number of magnetic lines provided by the field-magnet, (2) the number of copper conductors connected together upon the armature, (3) the speed at which these conductors are driven. In alternate-current dynamos the rate of cutting is continually changing in a regular periodicity; in continuous-current machines the rate of cutting is automatically averaged and made steady by the method of grouping the conductors around the ring or drum in a closed circuit, and connecting to the commutator. It is shown later, on p. 211, that, for continuous-current dynamos of the common two-pole type, the electromotive-force generated in the revolving armature may be calculated as follows:—

Let the speed of the armature, or revolutions *per second* be called n.

Let the number of conductors that are joined in series with one another around the armature be called C.

Let the number of magnetic lines which pass through the armature core from side to side be called **N**.

Let the number of volts of electromotive-force generated by the rotating armature be called E.

Then the following formula holds good:—

$$E = n \times C \times \mathbf{N} \div 100{,}000{,}000.$$

Example.—In a Kapp dynamo used at the Technical College, Finsbury, C = 120; **N** = 7,170,000; at a speed of 780 revs. per min., or 13 revs. per sec., the whole electromotive-force generated is 111 volts.

From the above formula it will be seen that the electromotive-force at which any dynamo is to deliver its current is the product of three factors; and it can be increased by increasing any one of the three, or all of them. In a given machine C is a constant, and **N**, the magnetic flux, cannot be increased beyond the capacity of the iron core to carry magnetic lines. But if it is desired to design a new machine, obviously any value might be assigned to any of the three factors, provided the product came to the required amount. It is, therefore, a question of expediency whether in so designing a machine we will increase any one of the factors rather than any other. To increase **N** means using a larger cross section of iron, and a correspondingly big field-magnet, and therefore involves additional cost of iron. To increase C means increasing the weight, and therefore the cost of the copper conductors, for the section of these depends on the current they have to carry, whilst the electromotive-force generated depends on their number, and on the rate at which they cut the magnetic lines. Moreover, experience shows that in thus increasing the quantity of copper upon an armature core of given size involves, when once a certain limit is reached, the very serious difficulty that the machine cannot be run without sparking at its brushes. To increase the speed n involves mechanical difficulties about lubrication and liability of the parts to fly out; in fact, mechanical considerations limit the speed. For many years modern practice has gone in the direction of keeping the speed slow, and in keeping down the relative amount of copper, the quantity of iron being relatively large; for not only so is the total cost of the machine less than it would be if the relative amounts of copper and iron were reversed, but the expense and trouble of maintenance is found to be less. Machines with a relatively massive and powerful field-magnet spark less, and require less attention to regulation and need fewer renewals of the brushes and commutator than do those which have a comparatively weak field-magnet. Of late there has been some tendency, however, to a movement in the opposite direction, because if, by special designing, without sacrificing the advantages attained in the possession of a relatively powerful field-magnet, the speed and the weight of copper on the armature can be increased; the output of such a machine will be proportionally augmented at a small increase of total weight and total prime cost.

For alternate-current machines the fundamental formula requires to be completed by the introduction of two additional factors. Such machines are usually multipolar, and if $\mathbf{N}$ represents the magnetic flux around any one of the individual magnetic circuits, the total magnetic effect must be increased by multiplying by the number p of pairs of magnetic poles that surround the armature. Further, a constant k must be inserted, the numerical value of which (varying from 1·8 to 2·5 in actual machines) depends on the relative breadths of the coils and pole-pieces employed. The general formula for the volts generated in any alternate-current machine will then be:—

$$\mathrm{E} = k \times p \times n\,\mathrm{C} \times \mathbf{N} \div 100{,}000{,}000.$$

Example.—In one of Kapp's alternators, $k = 2{\cdot}3$; $p = 6$; $\mathrm{C} = 1190$; $\mathbf{N} = 1{,}250{,}000$, when running at 700 revs. per min.; so that $n = 11{\cdot}6$, $\mathrm{E} = 2360$.

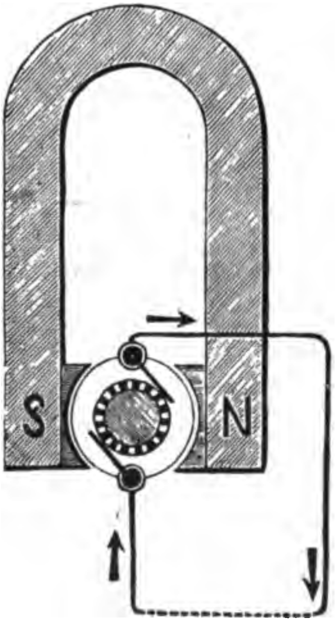
METHODS OF EXCITING THE FIELD-MAGNETISM.

The five simple methods of exciting the magnetism that is to be utilized in the magnetic field may be grouped under two heads, according to whether the armature of the machine supplies the machine's own magnetism or whether the magnetism is provided for from some other source.

Magneto-dynamo.—In the oldest machines there was no attempt to make the machine excite its own magnetism, which was provided for it once for all by the employment of a permanent magnet of steel. Unfortunately, the supposed permanent magnetism of steel magnets slowly decays, and is diminished by every mechanical shock or vibration to which the machine is subjected.

The *magneto-electric machine*, or *magneto-dynamo*, a diagrammatic drawing of which is given in Fig. 39, survives, indeed, in numerous small types of machines. It has the serious disadvantage of being both heavier and bulkier than other dynamos of equal capacity, because steel cannot be permanently magnetized to the same high degree as that to which wrought iron, or cast iron, or even steel itself, can be temporarily raised.

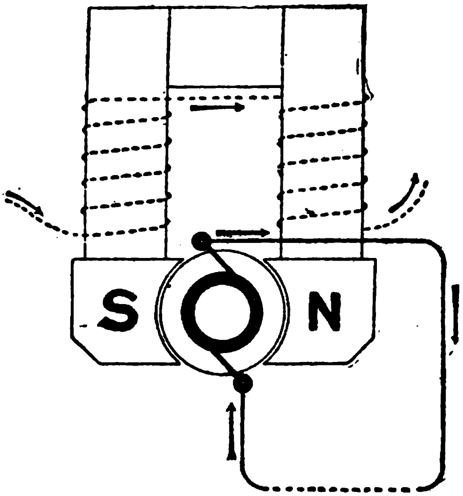
FIG. 39.



THE MAGNETO-DYNAMO.

Separately-excited Dynamo.—It was an obvious step to substitute for steel magnets, electromagnets excited by means of currents from some independent source such as a voltaic battery. The *separately-excited dynamo* (Fig. 40) comes therefore second in the order of development. Though used by Faraday, this method did not come into acceptance until, in 1866, Wilde employed a small auxiliary magneto machine to furnish currents to excite the field-magnets of a larger dynamo. The separately-excited dynamo, in common with the magneto machine, possesses the property that, saving for reactions due to the armature current, the magnetism in its field, and therefore the electromotive-force of the machine, is independent of changes of resistance going on in the working circuit.

FIG. 40.



THE SEPARATELY-EXCITED DYNAMO.

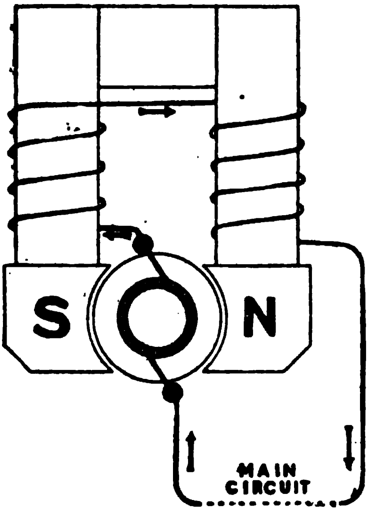
The dynamos of either of the preceding kinds can be governed, either by altering the speed or by altering the amount of magnetism that passes across the armature. For long it has been the fashion to control the electromotive-force of magneto machines by the device of providing a movable piece of iron, which could be placed more or less over the poles of the field-magnet, serving as a magnetic shunt to divert some of the magnetism from the armature. In the case of separately-excited machines there are two other methods of diminishing at will the effective magnetism, namely by weakening the exciting current, for example, by introducing more or less resistance into the exciting circuit, or by altering the number of turns of wire through which the existing current circulates around the field-magnet.

The simple methods of making dynamos self-exciting are three in number: (1) the whole current from the armature may be carried through field-magnet coils that are connected in series with the main circuit; (2) a portion of the current from the armature may be diverted from the main circuit and carried through field-magnet coils of somewhat high resistance connected as a shunt; (3) the current required to excite the field-magnet may be procured either from a second armature revolving in the same field, or (if the armature consist of many coils) from some of the coils of the armature that may be separately joined up for that purpose.

Series Dynamo.—The series-wound, or ordinary dynamo (Fig. 41), possesses but one circuit. It has the disadvantage of not starting action until a certain speed has been attained, or, unless the resistance of the circuit is below a certain limit; the machine refusing to magnetize its own magnets when there is too much resistance and too little speed. The least speed of self-excitation is a measure of the goodness of the magnetic circuit. Series-wound machines are also liable to become reversed in polarity, a serious disadvantage, and one that unfits this type of machine for employment in electro-plating or for charging accumulators. Any increase in the resistance of the series-wound dynamo lessens its power to supply current, because it diminishes the current in the coils of the field-magnet, and therefore diminishes the amount of the effective magnetism. When lamps are in series (as is usual in an arc-light circuit) in the circuit of a series-wound dynamo, the switching on of an additional lamp both adds to the resistance of the circuit and diminishes the power of the machine to supply current. On the other hand, when lamps are in parallel across a pair of mains fed by a dynamo, if that dynamo is series-wound, the switching on of additional lamps not only diminishes the resistance of the circuit, but causes the field-magnets to be further excited by the increased current, so that the more lamps are on, the greater becomes the risk of their getting too great a current.

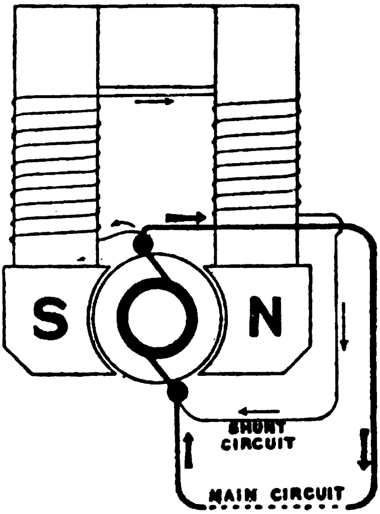
Shunt Dynamo.—In the shunt-wound machine (Fig. 42) the field-magnet is wound with many turns of fine wire, to receive only a small portion of the whole current generated in the armature. These coils are connected to the brushes of the machine, and constitute a by-pass circuit or shunt. Shunt machines are less liable to reverse their polarity than series machines. Owing to the somewhat greater cost of the fine wire of the shunt-coil, they are slightly dearer in prime cost than series machines of equal power, but the expenditure of electric energy to keep up the magnetism is practically alike in both cases. It requires the same expenditure of electric energy to magnetize an electromagnet to the same degree, whether the coil consists of many turns of thin wire or of a few turns of thick wire, provided the *volume* occupied by the coil be alike in the two cases, and provided the

FIG. 41.



THE SERIES DYNAMO.

FIG. 42.



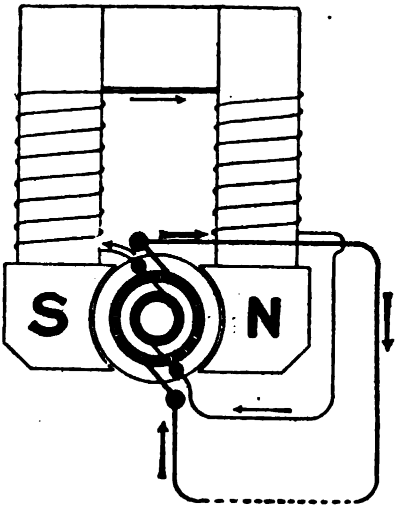
THE SHUNT DYNAMO.

insulation is relatively of the same thickness. When a shunt machine is supplying lamps in parallel, the addition of lamps which brings down the nett resistance of the circuit will increase the current, but not proportionally, for when the resistance of the main circuit is lowered, a little less current goes round the shunt and the magnetism drops a trifle; nevertheless, such a machine may regulate itself tolerably well if the internal resistance of its armature is very small. For a set of lamps in series, the power of a shunt dynamo to supply the needful current increases with the demands of the circuit, since any added resistance sends additional current round the shunt in which the field-magnets are placed, and so makes the magnetic field more intense. On the other hand, there is a greater sensitiveness to inequalities of driving, in consequence of the great self-induction in the shunt; and for machines giving high voltage shunt winding is too costly. The shunt part of the circuit in the present case consists of a fine wire of many turns wound upon iron cores. It therefore has a much higher coefficient of self-induction than the rest of the circuit; and, consequently, any sudden variations in the speed of driving cannot but affect the current in the main circuit more than in the shunt. Briefly, the shunt winding, though it steadies the current against perturbations due to changes of resistance in the circuit, does not steady the current against perturbations due to changes in speed of driving. The electromotive force of the shunt machine can be controlled by introducing a variable resistance into the shunt circuit.

A variety of the shunt method involves the use of a *third brush*, placed against the commutator at some point intermediate between the points of highest and lowest potential. The ends of the exciting coil are connected to the third brush and to one of the ordinary brushes, so that the exciting coil receives a fraction of the volts generated in the armature.

Separate-circuit Self-exciting Dynamo.—There is yet the third species (Fig. 43) of self-exciting machine, in which the field-magnet coils are arranged to form part of a circuit entirely separate from the main circuit, but are supplied with currents from coils rotating in the field. There are two ways of carrying this into effect: (1) a second armature may be made to rotate between the same field-magnets in order to supply the exciting current, each armature having its own commutator; machines on this plan were devised by Ladd[1] and by O. and F. H. Varley[2]; (2) a few of the armature coils may be connected up separately to a special commutator to supply an exciting current. Such systems were devised by Wilde, Holmes, and Lontin, about the year 1868 or 1869, in order to make their alternate-current machines excite themselves. Holmes described a machine having twenty helices in the armature, ten of which supplied alternate currents to the lamps, whilst the remaining ten, or any part of them, could be so connected up through a special commutator as to supply the exciting current to the field-magnets. Ruhmkorff attained the same end by winding a second wire upon the Siemens (shuttle-wound) armature, which then was provided

FIG. 48.



SEPARATE-CIRCUIT SELF-EXCITING DYNAMO.

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[1] *Phil. Mag.*, xxxiii. 544, 1867. [2] Specification of Patent, 2525 of 1869.

with a commutator at each end. Winkler's dynamo[1] is internally self-excited by a second separate winding. The effect of the separate-coil method of excitation is almost identical with that of the shunt method, but it has the advantage that the current thus taken off for magnetizing may be taken at a low voltage; this being preferable in the case of machines for high voltages. For machines working at 1000 volts and over, the cost of the fine wire for winding a shunt would be prohibitive.

Any of the five systems enumerated may be applied in direct-current machines. For alternate-current machines, neither series winding nor shunt winding is applicable. Each of these five systems of exciting the field-magnetism has its own merit for special cases, but none of them is perfect. Not one of these methods will ensure that, with a uniform speed of driving, either the electric pressure at the terminals or the current shall be constant, however the resistances of the circuit are altered.

If all the lamps in the circuit of a dynamo were required to be kept alight, all being turned on and turned off at once—in other words, if the output of the machine were constant—it would matter little how the magnetism of the field-magnet was excited, whether in main circuit or in shunt, provided the speed were kept constant. But for systems with a variable number of lamps, none of the simple methods of excitation enumerated above will insure regularity of pressure in the electric supply.

But though theory tells us that none of these systems is perfect, theory does not leave us without a guide. Thanks to various inventors, we have been taught how to combine these methods so as to secure in practice a machine which shall, when driven at a constant speed, give out its current at a constant pressure. These methods are carefully developed in Chapter XI. They are briefly described here also, so as to complete our summary of the methods of exciting the field-magnets.

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[1] *Electrical World*, xvii. 455, 1891.

COMBINATION METHODS.

The discovery of the method of rendering a dynamo machine automatically self-regulating when driven at a uniform speed, is due to M. Marcel Deprez, and is a result arising from the study of the diagrams of the characteristic curves of dynamos.[1] There are two distinct cases for which self-regulation is required.

As the first function of a dynamo in practice is to feed with sufficiency and regularity a system of lamps, and as those lamps are usually in practice[2] arranged either in parallel or in series, it is clear that in the former case a *constant electric pressure or "difference of potentials"* between the mains, and in the latter *a constant current* is required.

Suppose a dynamo to have an armature, without demagnetizing reactions, of zero internal resistance, and to have its field-magnets excited from some independent constant source. At a constant speed it would give a constant potential at its terminals whatever the resistance in the circuit. But if it has internal resistance, the external pressure will be less than the whole electromotive-force, and the discrepancy will be greater according as the internal resistance and the current are greater. Any resistanceless, separately-excited, or shunt dynamo would thus be self-regulating.

Now it is, we know, impossible to have an armature the resistance of which is zero. But if, knowing the resistance of the armature of our dynamo, we find out what additional magnetizing power is necessary to increase the working electromotive-force of the dynamo, so that the net electromotive-force (after discounting the part needed to overcome the internal resistance) shall be constant, and then, having found it out, provide for this variable part of the magnetization by putting on coils in series, our dynamo thus reinforced will act as if it had no internal resistance, and will give, within certain limits, a constant difference of potentials at its terminals.

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[1] See *La Lumière Electrique*, Dec. 3, 1881; and Jan. 5, 1884.

[2] Occasionally incandescent lamps are arranged with two, three, or more lamps in series, a number of such series being united in parallel across mains that are kept at a constant pressure. Less frequently a few lamps all in parallel with one another are inserted in the circuit of a series of arc lamps through which a current of constant strength is maintained. In any case, distribution must fall under one or other of the two cases considered.

For distribution *at a constant pressure*, we must have, therefore, dynamos in which there is a combination of *series* coils with some auxiliary independent constant excitation.

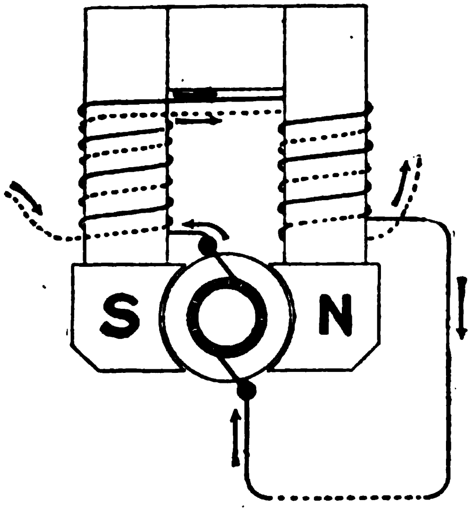
On the other hand, if a shunt dynamo were constructed, with an armature of considerable resistance, the electromotive-force which it would develop at a constant speed, would be nearly proportional to the external resistance, for doubling the external resistance would very nearly double the proportion of current thrown round the shunt, and therefore (always assuming the iron cores to be far from saturation) the magnetism of the field-magnet would be doubled; in other words, there would be an approximately constant current. In this case, a high internal resistance in the armature would not be economical, and the output of the machine would be very small in proportion to its weight; moreover, its magnetic state would be one of great instability. Consequently, it has been hitherto found impracticable to devise any mode of compound winding which will be self-regulating for a constant current. Other modes of regulation are resorted to in the case of machines for arc-lighting for which a constant current is needed. These are considered in Chapters XVII, and XXVII.

COMBINATION TO GIVE CONSTANT PRESSURE.

(1) *Series and Separate* (*Deprez*).—This method, illustrated in Fig. 44, can be supplied to any series dynamo, provided the coils are such that a separate current from an independent source can be passed through a part of them, so that there shall be an initial magnetic field, independent of the main-circuit current of the dynamo. When the machine is running the electromotive-force producing the current will depend partly on this independent excitation, partly on the current's own excitation of the field-magnets. If the

machine be run at such a speed that the quotient of the part of the electromotive-force due to the self-excitation, divided by the strength of the current, is numerically equal to the internal resistance of the machine, then the electromotive-force in the circuit will be constant, however the external resistances are varied. M. Deprez has further shown that this velocity can be deduced from experiment, and that, when the critical velocity has once been determined, the machine can be adjusted to work at any desired electromotive-force by varying the strength of the separately-exciting current to the desired degree.

Fig. 44.



Combination of Series and Separate.

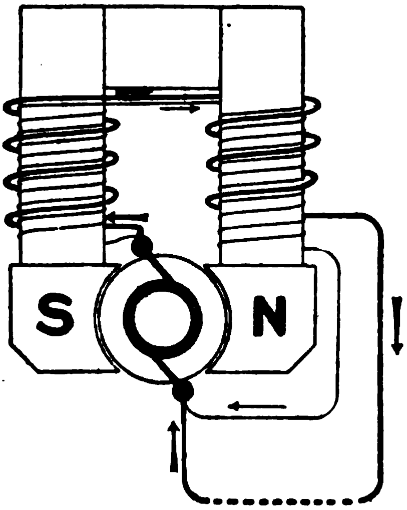
(2) *Series and Magneto* (*Perry*).—The initial electromotive-force in the circuit required by Deprez's theory, need not necessarily consist in there being an initial magnetic field of independent origin. It is true that the addition of a permanent magnet, to give an initial partial magnetization to the pole-pieces of the field-magnets, would meet the case to a certain extent; but Professor Perry has adopted the more general solution of introducing into the circuit of a series

dynamo a separate magneto machine, also driven at a uniform speed, such that it produces in the circuit a constant electromotive-force equal to that which it is desired should exist between the leading and return mains.

This arrangement may be varied by using a shunt-wound exciter, the magnets being, as before, included in the part of the circuit outside the machine. The combination of a permanent magnet with electromagnets in one and the same machine, is much older than the suggestions of either Deprez or Perry, having been described by Hjorth in 1854.

(3) *Series and Shunt.*—A dynamo having its coils wound, as in Fig. 45, so that the field-magnets are excited partly by the main current, partly by a current shunted across the brushes of the machine, has been used for some years past. An arrangement used by Brush[1] from 1878 made the machine

FIG. 45.



SERIES AND SHUNT.

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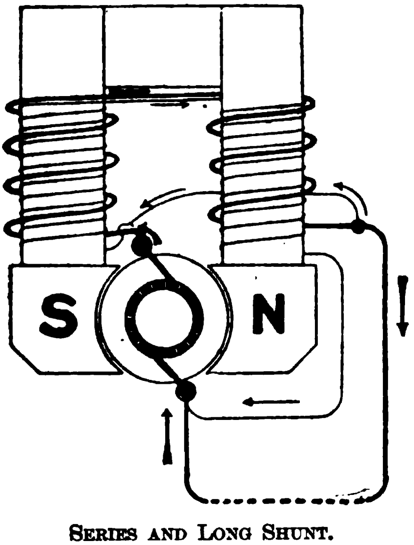
[1] The shunt part of the circuit, originally called the "teazer," was adopted at first in machines for electro-plating, with the view of preventing a reversal of the current by an inversion of the magnetization of the field-magnets, but was retained in some other patterns of machine on account of its usefulness in "steadying" the current.

into one that was very nearly self-regulating, there being less than one volt of variation in the pressure within a wide range of current. If the shunt coils be comparatively few, and of high resistance, so that their magnetizing power is small, the machine will give approximately a uniform pressure of but few volts; whereas if the shunt be relatively a powerful magnetizer, as compared with the few coils of the main circuit, the machine will be adapted for giving a constant pressure of a great number of volts; but, as before, each case will correspond to a certain critical speed, depending on the arrangements of the machine. The arrangement with shunt and series coils is commonly known as a *compound winding.*

(4) *Series and Long Shunt.*—In 1882 the author proposed to give this name to a combination closely resembling the preceding, which had not then, so far as he was aware, been actually tried for this purpose, though it had been, like the preceding, described by Brush. If, as in Fig. 46, the magnets are excited partly in series, but also partly by coils of finer wire, connected as a shunt *across the whole external circuit,* then the combination should be more applicable than

FIG. 46.



SERIES AND LONG SHUNT.

the preceding to the case of a constant electromotive-force, for the current through the long-shunt winding will be more constant than that through a short shunt connected across the brushes.

In 1882 it was the author's opinion that although the last two combinations were not such perfect solutions of the problem as those which precede, they were more likely to find an immediate application,[1] since they can be put into practice upon any ordinary machine, and do not require, as in the first two combinations, the use of separate exciters, or of independent magneto machines. This opinion has been fully justified in the great progress made subsequently in the "compound" self-regulating machines.

(5) *Series and Separate-Coil.*—This method has not, apparently, been tried for direct-current dynamos. For alternate current dynamos a modification of it has been tried by Zipernowsky with success, the "series" or main-circuit excitation being, in this case, replaced by an excitation derived from the main circuit by means of a small transformer. This system is explained in Chapter XXV.

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[1] The invention of the "series and shunt" winding is claimed for several rivals. Brush undoubtedly first used it commercially, but whether with any knowledge of all its advantages is doubtful. It has also been claimed by Mr. S. A. Varley on the strength of the machine described in his patent specification, No. 4905 of 1876, in which there were two circuits both of different resistance, both having coils wound on the field-magnets, and both going to the lamp. He has obtained a decision in the Scottish law courts that this strange arrangement anticipated that described by Brush. Compound winding was, however, described in 1871 by Sinsteden, in *Pogg. Annalen* (*Supplement-Band*, v.), 651. It was mentioned as having some advantages by Sir C. W. Siemens in *Philosophical Transactions*, March, 1880. It is also claimed for Lauckert (see note by M. Boistel, p. 100 of his translation of first edition of this work); Paget Higgs (*Electrical Review*, xi. 280, and *Electrician*, Dec. 23, 1882); J. W. Swan, see Bosanquet (*ib.*, Dec. 9, 1882); J. Swinburne (*ib.*, Dec. 23, 1882); S. Schuckert (*ib.*, Oct. 13, 1883). It is claimed in America by Edison; and it has been patented by Messrs. Crompton & Kapp (*ib.*, June 9, 1883). See also Hospitalier (*L'Electrician*, No. 20, 1882). Students should also consult a series of articles in *The Electrician*, vol. x., beginning Dec. 16, 1882, by Mr. Gisbert Kapp. Further, they should see a paper by Dr. Louis Bell in the *Electrical World*, xvi. 383, 1891.

CHAPTER IV.

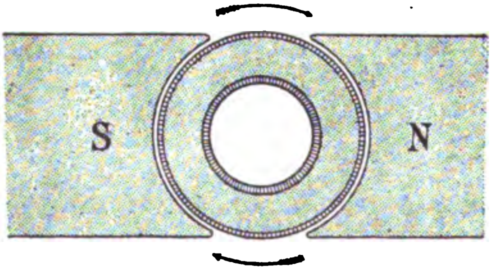
ACTIONS AND REACTIONS IN THE ARMATURE.

In this chapter we shall deal mainly with continuous-current dynamos with armatures of either ring or drum type, and having a simple magnetic field such as is furnished by the two-pole field-magnet so common in machines of this class.

For the sake of clearness we will suppose the armature (as viewed from the end to which the commutator is affixed), to be rotating right-handedly; and we will further suppose that the north-pole of the field-magnet is situated on the right hand, as in Figs. 39 to 46, so that the magnetic lines pass through the armature-core from right to left. We shall further suppose that the coils on the armature-cores are wound right-handedly. Taking this as a standard case it is afterwards very easy to see how a change in any one of these conditions will affect the induction of electromotive-force.

In Fig. 47 these points are illustrated by an end-view of a ring-armature. The magnetic lines proceeding from the N-pole will cross the adjacent gap-space from right to left, and enter the iron core of the armature; traversing this (as

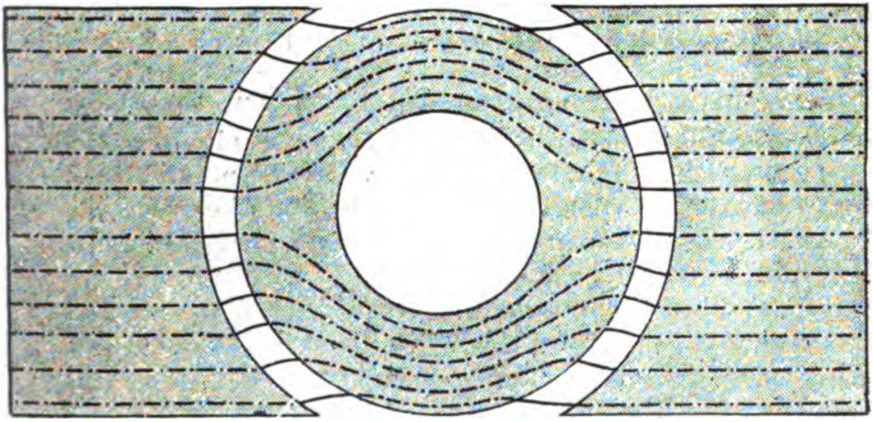
Fig. 47.



End-view of Armature between Two-pole Field-magnet.

in Fig. 48), they will then cross the other gap-space on the left and enter the S-pole of the field-magnet. The copper wires or conductors of the armature as each rises successively in the left-hand gap will cut these magnetic lines. Each conductor will emerge at the top of the gap, will move over the highest part of the armature from left to right, and in descending the gap-space on the right will again cut the magnetic lines. If we now apply the rule laid down on p. 22, we shall find that the directions of the induced electromotive-forces in these rotating conductors will be as follows:—In all the conductors as they *ascend* through the left-hand gap-space, the direction of the induced electromotive-force is *toward* the observer—whilst in all those that are *descending* the other gap-space on the right the induced electromotive-forces will be directed *from* the observer. If we assume that these electromotive-forces are actually producing currents,[1]

FIG. 48.



MAGNETIC LINES OF TWO-POLE DYNAMO (UNDISTURBED BY ANY CURRENT IN ARMATURE).

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[1] In all dynamos, when used as *generators*, the currents being set up by the electromotive-forces are of course in the *same direction* as the electromotive-forces which impel them. But it must be remembered that in the case of machines that are used as *motors* the currents are being sent in by superior electromotive-forces from outside, and that the induced electromotive-forces in the motor's armature, are always in an *opposite direction* to that of the current that is flowing.

then we may say that the currents flow toward the observer in the conductors which are rising in the left gap-space; and from the observer in those that are descending the right gap-space. If the armature is wound as a ring, the currents which come in one direction in the gap-space return in the other direction down the inside of the ring. If the armature is wound as a drum, then the currents simply cross at the end of the core through connecting conductors provided for the purpose.

Now consider the way in which the coils on the armature are connected together. Whether wound as ring or drum they are grouped symmetrically around a symmetrical core, and united together into one closed coil; whilst at regular intervals along the windings, connecting pieces lead down to the separate bars of the commutator. Fig. 34, p. 40, shows a simple ring-winding, consisting of 32 turns of wire grouped in eight "sections" or groups, each consisting of four turns. The end of each section is joined to the beginning of the next, all the way round. There are eight bars in the commutator, and each section of the winding is connected down at its ends to two adjacent bars of the commutator. In Fig. 34, the brushes are represented as making contact respectively with the highest and lowest bars of the commutator. As the windings on the ring are right-handed a little consideration will show, in accordance with the preceding paragraphs, the induced currents in the ascending windings on the left-hand half of the ring will all be climbing from the lowest point to the highest; and also the currents in the right-hand half of the ring will also be climbing from the lowest point to the highest. These two currents will unite at the top bar of the commutator, and will flow together into the upper brush (which will accordingly be deemed the positive brush), and thence will go to supply the external circuit; after which the current will return to the lower, or negative brush, and will there re-enter the armature at the lowest bar of the commutator, dividing again into two parts and flowing up the two halves of the winding as before. If the conductors on the armature were wound (or connected) left-handedly, the lower brush would be the positive one, and the upper the negative. All the preceding argument would equally apply to a drum-winding, but, owing to the overlapping of the two halves of the windings, the paths of the currents would not be quite so obvious.

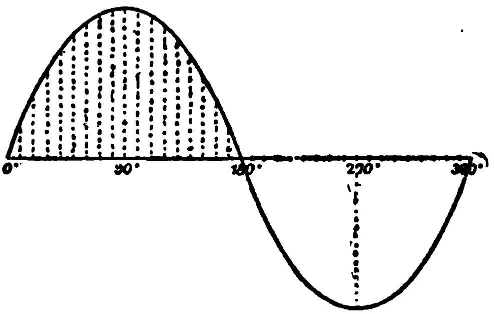
It will be noted that the current after having entered the armature coils and divided into its two paths goes from section to section without going down into any of the commutator bars until both streams unite at the other side and pass down into the bar of the commutator which is for the moment passing under the brush. At those moments when one of the commutator bars is just leaving contact with a brush, and another one is coming into contact with it, the brush will rest on two adjacent bars and will momentarily short-circuit one section of the coils. While this lasts the two streams that come through the two halves of the winding will flow respectively to the two bars of the commutator, and will thus unite by both flowing into the same brush.

It is evident that if the magnetic lines in the gap-space are more closely crowded together in one part than in another, the electromotive-forces induced in the separate windings as they cut these magnetic lines will be of unequal amount; the greatest electromotive-force being generated in those conductors which are passing through that part of the magnetic field where the lines are crossing the gap most densely. But whatever the electromotive-forces are in the individual conductors, since these are all united together, end to end, it will be obvious that the total electromotive force of either half of the winding, from brush to brush, will be the sum of the electromotive-forces in the separate coils. As this is a point of importance it must be followed out with some care.

INDUCTION IN A UNIFORM HORIZONTAL MAGNETIC FIELD.

In considering the case of an ideal simple dynamo, it was shown that the induction in the rotating loop or coil was zero at the position where it lay in the diameter of commutation, and that the induction increased (as the sine of the angle) to its maximum value at about 90° (see Fig. 18, p. 32). This is of course true for the ideal case of the magnetic lines going straight across horizontally with equal density everywhere. In actual dynamos the distribution of magnetic lines in the gap is different, not always symmetrical, as we shall see. Returning to the ideal case, Fig. 49, which presents a curve of *sines*, will serve to represent, by the height of the curve, the amount of induction going on in an armature at every 10° round the circle. If there are, for example, thirty-six sections in a ring armature, so that the sections are spaced out at 10° apart, the least active sections will be those at 0° and 180°, whilst the most active are those at 90° and 270°. But in all the ordinary "closed-coil" armatures, the separate sections are connected together so that any electromotive-force induced in the first section is added on to that induced in the second, and that in the third is added to these two, and so on all the way round to the brush at the other side. The separate electromotive forces are added together just as are the separate electromotive-forces of a battery of voltaic cells united in series. A ring of battery cells united in series, but having one-half the cells set so that the current in them tends to run the other way round the ring, forms a not inapt illustration of the inductions in the sections of a ring armature. If it could be indicated that those sections which

FIG. 49.

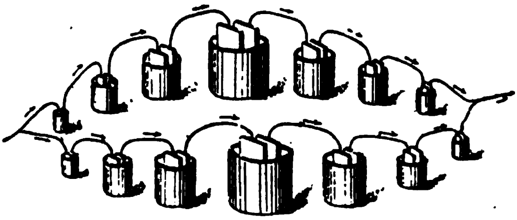


CURVE OF INDUCED ELECTROMOTIVE-FORCE.

are at 90° from the brushes are much more powerful in their inducing effect than those that occupy positions near the brushes, the analogy would be still more perfect.[1]

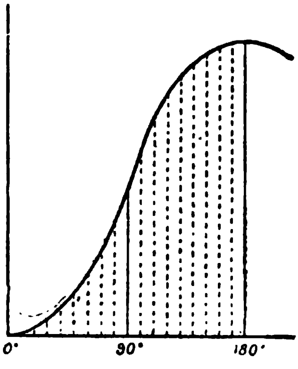
Now, knowing how the induction in individual coils or sections rises and falls round the ring, let us inquire what this will result in when we add up the separate electromotive-forces, so as to find the total effect. We shall have to add up the effects of all the sections round, from the negative brush at 0° on one side, to the positive brush at 180° on the other side; and the result will be the same in each half of the ring because of symmetry. Suppose we take the side from 0° by 90° to 180° (on the left in Figs. 20 and 47). If we look at the curve given above (Fig. 49), we shall see that as the heights of the dotted lines represent the amount of induction, the total effect will be got by adding up the lengths of all those from 0° to 180°; and of course, the sum is equal to the sum of the negative lengths between 180° and 360°. But we may do the thing in another way, which beside giving us the final total, will

FIG. 50.



RING OF CELLS: THE TWO HALVES IN PARALLEL.

FIG. 51.



INTEGRATED CURVE OF POTENTIALS.

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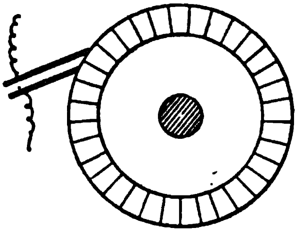
[1] In Fig. 50 the middle cells of each row are drawn larger to suggest this; only, unfortunately, *large* cells do not possess a higher electromotive-force than small ones, though they have less resistance internally.

show us how the sum grows as each length is successively added on. We should find that the sum grew slowly at first, then rapidly, then slowly again as it neared its highest value. The sum of the effects would grow, in fact, in a fashion represented on a reduced scale in the curve of Fig. 51. This process of adding up a continuously-varying set of values is called by mathematicians integrating. Fig. 51 is got by integrating the values of the curve Fig. 49 between the limits of 0° and 180°. Now in the actual dynamo this integration is effected by the very nature of things, in consequence of the fact that each section is united to those on either side of it.

It is possible to investigate by experiment both these effects;[1] the induction in the individual coils, and the total or integrated potential. Several methods have been suggested for measuring the electromotive-forces, and as each has some advantages, they will be separately described.

S. P. Thompson's Method.—The electromotive-force induced in a single section as it passes any particular position, may be examined by means of a voltmeter or potential-galvanometer in the following way. Two small metal brushes are fixed to a piece of wood at a distance apart equal to the width between two consecutive bars of the commutator. These brushes are united by wires to the voltmeter terminals, so that any difference of potentials between them will be indicated on the dial of the instrument. The two brushes are placed against the collector, as shown in Fig. 52, while it rotates; and as they can be applied at any point, they will give on the voltmeter an indication which measures the

FIG. 52.



METHOD OF EXPERIMENTING AT COMMUTATOR OF DYNAMO.

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[1] For some investigations made by the author, the reader is referred to the Author's *Cantor Lectures* delivered in 1883 before the Society of Arts, and which are also described in the earlier editions of this book. The reader should refer to curves of induction obtained by Gaugain (see *Annales de Chimie et de Physique*, 1873), and by Isenbeck (see *Elektrotechnische Zeitschrift*, *Aug.* 1883).

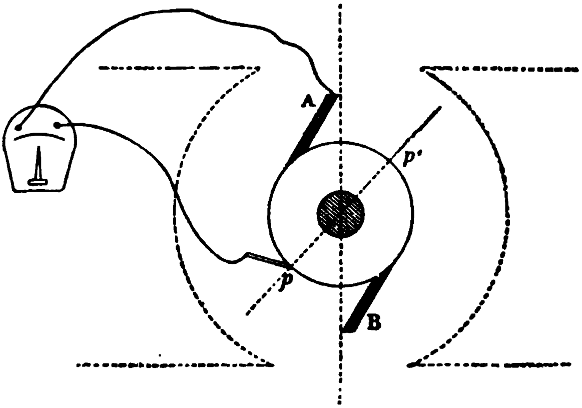
amount of electromotive-force in that section of the armature which is passing through the particular position in the field corresponding to the position of the contacts. The author found, in the case of a small Siemens dynamo which he examined, that the difference of potential indicated was almost *nil* at the sections close to the proper brushes of the machine, and was a maximum about half-way between. In fact, the difference of potentials rose most markedly at 90° from the usual brushes, or precisely in the region where, as seen in Fig. 49, the induction is theoretically at its highest point, and where, as seen in Fig. 51, the slope of the curve of total potential is greatest.

Method of Shifting Armature.—After the experiment above detailed, the author experimented on his Siemens dynamo in another way. The machine was dismounted, and its field-magnets separately excited. Two consecutive bars of the commutator were then connected with a reflecting galvanometer having a moderately heavy and slow-moving needle. A small lever clamped to the commutator allowed the armature to be rotated by hand through successive angles equal to 10°, there being thirty-six bars to the commutator. The deflections obtained, of course measured the intensity of the inductive effect at each position. The result confirmed those obtained by the method of the two wire brushes.

Mordey's Method.—The rise of the totalized (*i. e.* "integrated") potential round the armature can be measured experimentally by a method first suggested by Mr. W. M. Mordey, and also involving the use of a voltmeter. One terminal of a voltmeter was connected to one of the brushes, A, of the dynamo (Fig. 53), and the other terminal was joined by a wire to a small pilot brush, *p*, which could be pressed against the rotating collector at any desired part of its circumference. In a well-arranged continuous-current dynamo thus, if one measures the difference of potential between the negative brush and the successive bars of the commutator, one finds that the potential increases regularly all the way round the armature, in both directions, becoming a maximum at the opposite side where the positive brush is. Mr. Mordey found that this distribution is irregular in badly designed machines.

The author then made the suggestion that these indications might with advantage be plotted out round a circle

FIG. 53.



MORDEY'S METHOD OF EXPLORING THE POTENTIALS AROUND THE COMMUTATOR.

corresponding to the circumference of the commutator. Figs. 54 and 55, which are reproduced from his Cantor Lectures, serve to show how the potential in a good Gramme machine rises gradually from its lowest to its highest value.

FIG. 54.

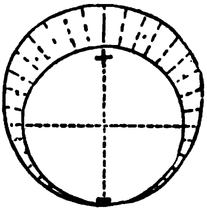
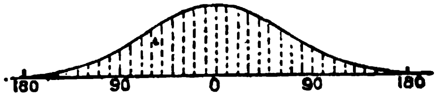


DIAGRAM OF POTENTIAL ROUND THE COMMUTATOR OF GRAMME DYNAMO.

FIG. 55.



HORIZONTAL DIAGRAM OF POTENTIALS AT COMMUTATOR OF GRAMME DYNAMO.

It will be seen that, taking the negative brush as the lowest point of the circle, the potential rises perfectly regularly to a maximum at the positive brush. The same values as are plotted round the circle in Fig. 54 are plotted out as vertical ordinates upon the level line in Fig. 55, which is nothing else than Fig. 51 completed for both halves of the commutator. Fig. 51 is, however, a theoretical diagram of what the distribution ought to be, whilst Fig. 55 is an actual record taken from an "A" Gramme. If the magnetic field in which the armature rotated were uniform, this curve would be a true "sinusoid," or curve of sines. The steepness of the slope of the curve at different points will enable us to judge of the relative idleness or activity of coils in different parts of the field. The points marked + and — are close to the points of least sparking, or *neutral points.*

The rise of potential is not equal between each pair of bars, otherwise the curve would consist merely of two oblique straight lines, sloping right and left from the neutral point. On the contrary, there is very little difference of potential between the commutator-bars immediately adjoining either of the neutral points. The greatest difference of potential occurs where the curve is steepest, at a position nearly 90° from the brushes, in fact, at that part of the circumference of the commutator which is in connexion with the coils that are passing through the position of best action. Were the field perfectly uniform and parallel, the number of lines of force that pass through a coil ought to be proportional to the sine of the angle which the plane of that coil makes with the resultant direction of the lines of force in the field, and the rate of cutting the lines of force should be proportional to the cosine of this angle. Now the cosine is a maximum when this angle = 0°; hence, when the coil is parallel to the lines of force, or at 90° from the brushes, the rate of increase of potential should be at its greatest—as is very nearly realized in the diagram of Fig. 55, which, indeed, is very nearly a true "sinusoidal" curve. Such curves, plotted out from measurements of the distribution of potential at the commutator, show not only where to place the brushes to get the best effect, but enable us to judge of the relative "idleness" or "activity" of coils in different parts of the field, and to gauge the actual intensity of different parts of the field while the machine is running. As we shall see, the current in the armature reacts on the magnetic field, and distorts the distribution of magnetic lines in the gap-space. If the brushes are badly set, or if the pole pieces are not judiciously shaped, the rise of potential will be irregular, and there will be maxima and minima of potential at other points. An actual diagram, taken from a dynamo in which these arrangements were faulty, is shown in Fig. 56 and again is plotted horizontally in Fig. 57; from which it will be seen, not only that the rise of potential was irregular, but that one part of the commutator was more positive than the positive brush, and another part more negative than the negative. The brushes, therefore, were not getting their proper difference of potential; and in part of the coils, the currents were actually being forced against an opposing electromotive-force.

FIG. 56.

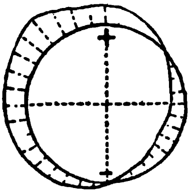
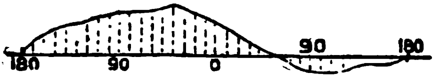


DIAGRAM OF POTENTIAL ROUND THE COMMUTATOR OF A BADLY-ARRANGED DYNAMO.

FIG. 57.



HORIZONTAL DIAGRAM OF POTENTIALS AT COMMUTATOR OF FAULTY DYNAMO.

This method of plotting the distribution of potential round the commutator has proved very useful in practice, and elucidates various puzzling and anomalous results found by experimenters who have not known how to explain them.

Curves similar to those given can be obtained from the commutators of any continuous-current dynamo having a closed-coil armature. The open-coil machines used in arc lighting give widely different curves owing to the peculiar arrangements of their commutators. It is of course, not needful in taking such diagrams that the actual brushes of the machine should be in place, or that there should be any circuit between them, though in such cases the field-magnets must be separately excited. It should also be remembered that the presence of brushes, drawing a current at any point of the collector, will alter the distribution of potential in the collector; and the manner and amount of such alteration will depend on the position of the brushes, and the resistance of the circuit between them.

Curves showing the actual distortions due to the armature reaction have been given by von Gaisberg[1] for a Schuckert dynamo, by Kohlrausch[2] for a Lahmeyer dynamo, and by M. E. Thompson[3] for a Thomson-Houston dynamo; also by Ryan (see below).

Swinburne's Method.—An elegant modification of the preceding method consists in connecting a high-resistance wire across the terminals of the machine, and finding by a detector galvanometer the positions along this wire of the points which have the same potential as that of the pilot-brush on the commutator. Being a zero method it is very accurate; and it dispenses with the voltmeter, which for the preceding method must be accurate over a wide range.

Joubert's Method.—Another mode of examining the electromotive-force induced at every successive point in the rotation was devised by M. Joubert,[4] who placed on the shaft of the dynamo a pair of insulated metal collars connected to the ends of the armature winding; each collar having a projecting contact piece which at each revolution made a moment contact against a spring. The moment at which this occurred depended upon the position of the contact springs, which could be adjusted to different points, and thus enable measurements to be made of the instantaneous values of the electromotive-force at all different positions of the armature. Joubert's method has been used, with some modifications, by Mordey and Raworth[5] and by Ryan.[6]

Mordey's Statical Method.—Another method, applicable to machines at rest and without currents in the armature, consists in separately exciting the field-magnets, while the armature coils, or any one of them, are connected to a suitable ballistic galvanometer, and observing the throw caused by the sudden turning off of the current in the exciting circuit. If this is done in a number of successive positions of the armature, relatively to the field-magnet, a measure is obtained of the intensity of the magnetic flux, corresponding to each position of the armature, and the result may be plotted out in a curve exhibiting the distribution of magnetism in the field. This distribution is however perturbed, as we shall see, when the machine is running by the current in the conductors of the armature.

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[1] *Elektrotechnische Zeitschrift*, vii. 67, Feb. 1886.

[2] *Centralblatt für Elektrotechnik*, ix. 419, 1887.

[3] *Electrical World*, xvii. 392, 1891.

[4] *Annales de l'Ecole Normale*, x. 131, 1881.

[5] *Journal Inst. Electrical Engineers*, xviii. 670, 1889.

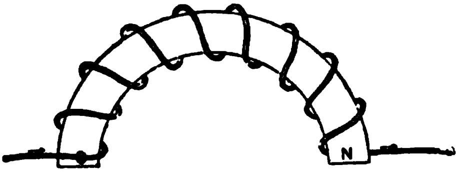
[6] *Trans. Amer. Instit. Electrical Engineers*, vii. 3, 1890.

REACTIONS DUE TO THE CURRENTS IN THE ARMATURE.

When a dynamo is running, a set of entirely new phenomena arises in consequence of the magnetic and electric reactions set up between the armature and the field-magnets, and between the separate sections of the armature coils. The current circulating in the armature windings produces magnetizing effects which interfere with those of the exciting currents of the field-magnet. In addition to this there may also be eddy-currents in the masses of metal which will perturb the magnetic field. The reactions of the running armature manifest themselves in several ways, the more important of which are (*a*) a tendency to cross-magnetize the armature; (*b*) a tendency to spark at the brushes; (*c*) hence the necessity of shifting the brushes through a certain angle to such a point that sparking disappears; (*d*) a consequent tendency for the armature current to demagnetize; (*e*) variations of sparking, and consequently of the neutral points, when the amount of current drawn from the machine is altered; (*f*) heating of armature cores and coils; (*g*) heating of the pole-pieces of the field-magnets; (*h*) a consequent discrepancy between the quantity of mechanical horse-power imparted to the shaft and the electric horse-power furnished in the electric circuit. The nature of these reactions demands careful attention.

Cross-magnetizing tendency of Armature Current.—We have seen (pp. 66, 67, and Fig. 50) that any closed-coil armature may be regarded as acting like a double voltaic battery, the two sets of coils acting like two rows of cells united "in parallel." We have now to show that a ring armature may be regarded also as a double magnet. Suppose a semi-ring of iron to be surrounded, as in Fig. 58, by a coil carrying a current, it will become, as every one knows, a magnet having a N. pole at one end, and a S. pole at the other. If a complete ring be similarly over-wound, but with an endless winding, and if then electric currents from a battery or other source are introduced into this coil at one point, flowing round the two halves of the ring to a point at the other side, and then leave the coil by an appropriate conductor, each half of the ring will be magnetized. There will be, if the currents circulate, as represented by the arrows in Fig. 59, a double S. pole at the point where the currents enter, and a double N. pole at the place where the currents leave (compare with p. 123). The currents circulating in a Gramme ring, will therefore tend to magnetize the ring in this fashion. Let us see how such a magnetization is distributed inside the iron itself. Fig. 60 shows the general course of the magnetic lines of force as they run through the iron; where they emerge into the air are the effective poles of the ring regarded as a magnet. Fig. 60 should be very carefully compared with Fig. 59. It will be noticed that though the majority of the lines of force pass externally into the air at the outer circumference, a few of the lines of force find their way across the interior of the ring, from its N. to

FIG. 58.

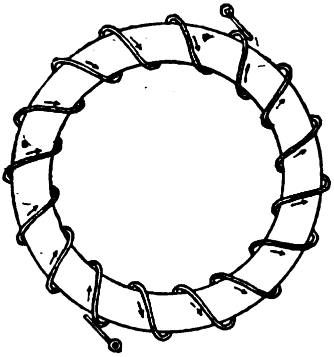


POLES OF HALF-RING.

its S. pole. This part of the magnetic field would in an actual dynamo be deleterious if the number of lines of force were not in reality few. The presence of the external masses of iron at the polar parts of the field-magnet tends to cause these magnetic lines to find their way externally.

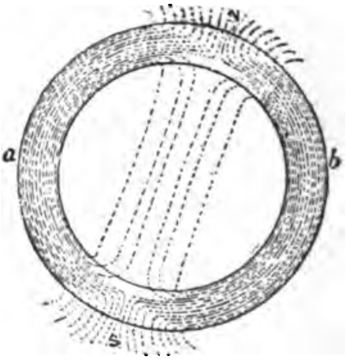
It is evident that this cross-magnetizing effect will produce a distortion of the magnetic field in the pole-pieces and in the gap-space; and it would only slightly diminish the electromotive-force of the machine if the brushes were to remain at the ends of a diameter exactly symmetrically between the two poles of the field-magnet. For reasons presently to be considered this is not possible. To obviate sparking the brushes have to be displaced into an angular position, the diameter of commutation being oblique when the brushes are so set at the neutral points; and when this is done the armature current produces, as we shall see, not only a cross-magnetizing effect, but also a demagnetizing effect; and this weakens the electromotive-force.

FIG. 59.



CIRCULATION OF CURRENT AROUND RING ARMATURE.

FIG. 60.



MAGNETIC FIELD DUE TO ARMATURE CURRENT.

Fig. 61 represents[1] the magnetic flux through an armature at rest, when the field-magnets are separately excited. The width of the gap-space is exaggerated, and the conducting wires both on the armature and on the field-magnet are shown in section as if consisting of a single layer of large round wires. Wires in which a current flows *toward* the observer are distinguished by a central dot. Wires in which a current flows *from* the observer are distinguished by a cross.

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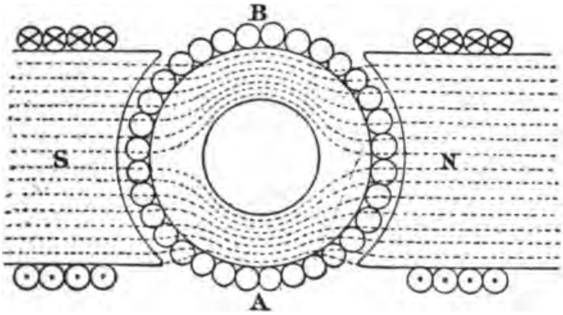
[1] Figs. 61, 62, 63, and 69 are taken, with some modification, from Esson's paper in *Journal Inst. Electrical Engineers*, xix. 135, 1890.

FIG. 61.

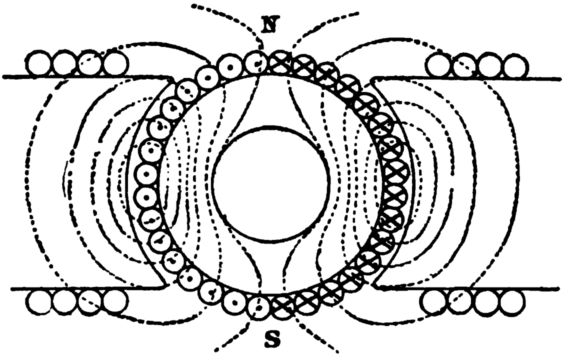


MAGNETIC FLUX THROUGH ARMATURE, WHEN NO CURRENT IS FLOWING.

The reader may think of the dot as representing the point of an arrow advancing towards him; whilst the cross may represent its retreating tail. Wires carrying no current are left blank. It will be noticed that the magnetic lines are fairly uniformly distributed both in the gap-spaces and in the polar portions of the field-magnet. The armature is drum-wound, the wires being only on the outside: the magnetizing effect of a current in it will be of the same kind as that traced out above in the case of a ring-wound armature, though less in degree.

Suppose now the exciting current in the field-magnet coils to be removed, and a current sent through the armature coils only, so as to imitate the effect of the current generated by the machine when running. If it is to do this, and if the armature connexions are in right-handed order, and the machine rotating right-handedly, the currents in both sets of windings will tend to climb toward the top, the upper brush being the positive brush, and the double-pole created there will be a north-pole. Suppose the brushes by which the current enters and leaves to be set respectively at the highest and lowest points, as in Fig. 62; then the dotted lines may be taken as representing the flow

FIG. 62.

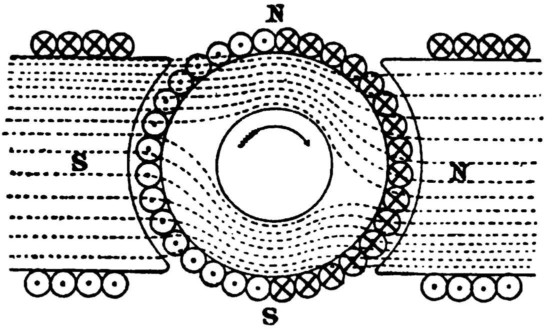


CROSS-MAGNETIZING EFFECT OF THE ARMATURE CURRENT.

of magnetic lines through the system. Since the number of such magnetic lines depends upon the goodness of the mag-

' 3

FIG. 62.



JOINT MAGNETIZING EFFECT OF CURRENTS IN FIELD-MAGNET AND ARMATURE (no lead).

netic path which they have to follow, it is clear that the cross-field produced by a given current, flowing in a given set of conductors, will be greater the narrower the gap-space, and the wider the arc spanned by the polar masses of iron[1] on either side.

But in an actual dynamo, when generating a current, both these magnetizing actions are going on at once. If we superpose Fig. 62 on Fig. 61 we shall obtain an approximate picture of the state of things, as Fig. 63. We supposed that the brushes were set to touch at two points on the vertical diameter. The field-magnets tend to magnetize the ring so that its extreme left point is a N. pole, and the currents tend to magnetize it so that its highest point, where the brush is, is a N. pole. The consequence of this will be a resultant magnetization in an oblique direction. Draw a line O F (Fig. 64) to represent the magnetizing force due to the field-magnets, and a line O C at right angles to represent the magnetizing force due to the armature current, then the diagonal O R of the parallelogram will represent the direction of the resultant magnetization. Draw a circle round O, and the point N will show how far the resultant induced magnetism is shifted round from the horizontal line. The magnetism is thus distorted in the direction of the rotation (in motors it is distorted the other way) as if the rotation of the armature had actually dragged the magnetism round a little. The position of maximum potential will also be shifted a little in the direction of the rotation. Now for reasons to be shortly discussed, when the magnetism is thus distorted, the *neutral points* (*i. e.* the points to which the brushes must be set so as to reduce sparking to a minimum) are found to have been also shifted forward. If for the present we assume that the brushes must be advanced through an angle equal to that through which the resultant magnetization has been turned, then O C must be altered till it is at right angles to O N. But shifting O C will itself alter N a little. We can find out easily the new position. On O F (Fig. 65) describe a semicircle, and set off F R, equal to the length that O C is to be, as a chord. Draw O C parallel and equal to F R; and draw also the diagonal O R as before. The angle C O N is now a right angle, and N is very nearly where it was before. If O V be a vertical line, then angle V O C = angle F O R is the angle of lead,

---

[1] Since these polar masses constitute the path by which the magnetic lines of the cross-field return on themselves, it is obvious that the cross-magnetization can be partially counteracted by dividing the polar masses by gaps running horizontally. See *Journal Inst. Electrical Engineers*, xx. 290, 1891.

FIG. 64.

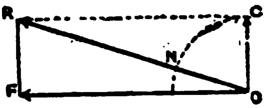
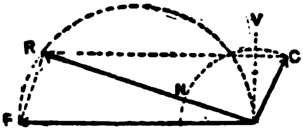


FIG. 65



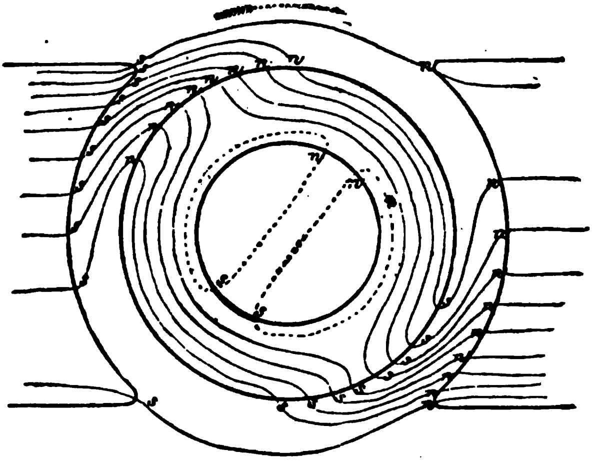
and if O F represents the magnetizing force of the field-magnets, and O C that of the armature current, then

$$\frac{O\,C}{O\,F} = \sin C\,R\,O = \sin F\,O\,R,$$

or the sine of the angle of lead is proportional to the ratio of the two magnetizing forces.

All this rearrangement of the lead is supposed to have been done in Fig. 66, which relates to a ring-wound dynamo. But a reference to Figs. 63 and 66, will also show that the magnetism of the armature reacts on the magnetism of the pole-pieces. The magnetic lines in the iron of the left pole-piece are crowded up towards the top corner, and in the right pole-piece are crowded toward the bottom, as if the polarity had been attracted upwards on one side and downwards on the other. The density of the field is completely changed from what it was in Fig. 61. The magnetic lines at the upper left side are crowded together and twisted across. The resultant N. pole of the ring—marked *n*, *n*, *n*, where the lines emerge from the ring—attracts the S. pole—marked *s*, *s*, *s*, where the lines enter the field-magnet—and the steam-engine which drives the dynamo has to do hard work in dragging the armature round against these attractions. The stronger the current in the armature coils, the stronger will be the poles in the armature, and the stronger will be the attraction of *n*, *n*, *n*, toward *s*, *s*, *s*; so the steam-engine must work still harder to keep up the speed. It will also be noticed in this figure which relates to a ring-wound machine that a *few* of the magnetic lines due to the current in the armature—two of them are shown dotted in the figure—leak across internally and contribute nothing to the external field. The oblique direction of this internal field marks the angle of lead of the brushes. It will be remarked that the innermost layers of iron of the ring are magnetized differently from the outermost, for the "*n*" pole of the outer layers of iron occupies a region lying obliquely on the left, while the "*n*" pole of the inner layers lies to the right of the highest point. All these phenomena—the shifting of the field—its concentration under the "leading" polar horn—its weakening under the "trailing" horn—the weak internal field—the discrepancy between the positions of the induced poles on the inner and outer sides of the ring, can all be observed in an actual dynamo. Fig. 67 shows the pattern produced experimentally in iron filings by placing a magnetized ring between the poles S N of a field-magnet, which would tend to induce in it poles *n'*, *s'*, and giving its own poles *n*, *s*, the proper lead. It should be compared with

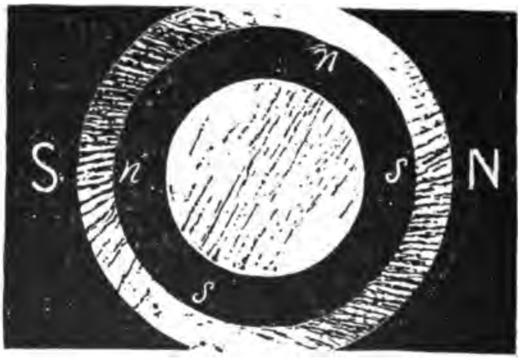
FIG. 66.



MAGNETIC REACTIONS BETWEEN FIELD-MAGNETS AND ARMATURE IN GENERATOR.

Figs. 63 and 66. It may perhaps be objected that in Fig. 66 the internal poles marked do not lie exactly at right angles to the external poles of the ring. Nor do they in actual dynamos. The position of the internal poles is determined by the lead given to the brushes, and *the brushes are so set that the dynamo shall not spark.*

Fig. 67.



Field of Two-pole Dynamo.

In the case of drum-wound armatures, the phenomena, though of the same kind as with ring windings, are a little less easily traced. In consequence of the over-wrapping of the windings on the outside of the armature, the currents in some of the windings are partially neutralized in their magnetizing effect on the core by those that lie across them, and consequently the polarity due to the current is not so well marked as with ring armatures. Neither can there be any considerable internal field. In fact drum armatures are less liable to induction troubles of all kinds than are ring armatures. But, with these exceptions, the same considerations apply to drums as to rings.

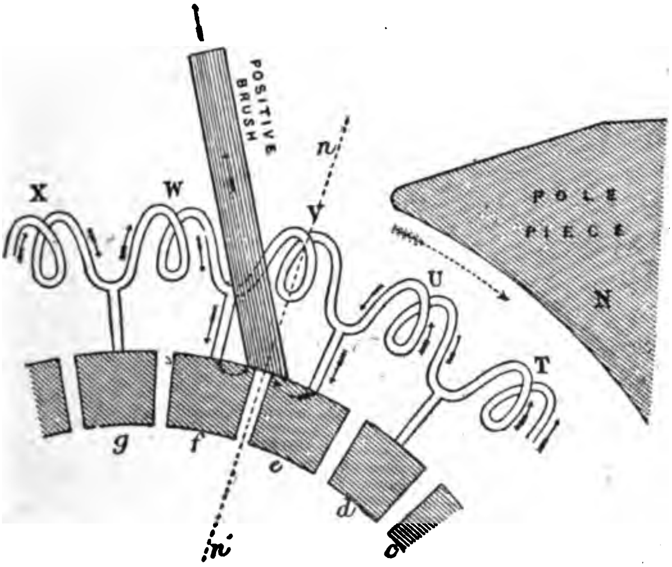
Neutral Points.—From the earliest time that dynamos have been used, engineers have found that, in order that the sparking may be a minimum, the brushes must be placed in certain positions, to be found by trial, called the *neutral points.* In ordinary two-pole dynamos the two neutral points lie at opposite ends of a diameter, which diameter is therefore called the *neutral line.* The term *diameter of commutation* ought to be reserved to denote the position actually occupied by the brushes, or by the coils that are passing the brushes, whether at the neutral point or not. Experience shows that in almost every case the neutral line is not exactly at right angles to the line joining the middles of the two pole-pieces, but lies obliquely across, being (in a generator) shifted round a few degrees in the direction of rotation. It was early found that in many machines the exact position of the neutral point was different according to the work that the dynamo was doing. If the brushes were set so as not to spark when a certain number of lamps were alight, then if the load of lamps was altered the machine sparked unless the brushes were adjusted to the corresponding neutral points. Hence arose the practice of mounting the brushes on *rockers* (see p. 35) by means of which their line of contact could be altered forward or backward to the neutral point. Great attention has naturally been paid by constructors to the practical problem how to get rid of variations in the angle of lead. On p. 71 it was stated that the neutral points lie close to the points of maximum positive and maximum negative potential on the commutator. But they are found not to coincide exactly with those points. At the point of maximum potential there is usually some sparking. The point of maximum potential has, as just shown, a forward lead, but the point of least sparking, the true *neutral* point, lies a little forward of this, this increased lead being due to another of the reactions now under consideration.

Causes of Sparking.—Whenever a circuit in which a current is flowing is suddenly parted, a spark is observed, particularly if that circuit contains an electromagnet or any coils of wire surrounding an iron core. The reason of the spark at break of circuit is as follows:—We know that every electric current possesses a property sometimes called "electric inertia," sometimes called "self-induction," by virtue of which it tends to go on. Just as a fly-wheel once set in motion tends to go on spinning, so a current circulating round a coil tends to go on circulating, even though the connexion with the source be cut off. True, the current lasts in most cases only for a small fraction of a second, but it *tends* to go on. It is also known that this quasi-inertia is connected with its magnetic properties, and that it is in the current's own magnetic field that this inertia of self-induction resides.

A current circulating round an iron core has a much greater electric inertia (or self-induction), because it has a more intense magnetic field, than one without an iron core. It requires an expenditure of energy to *start* a current because of this property; and that energy may be considerable. The electric current circulating in a coil possesses energy, and if we stop it by opening the circuit, that energy will show itself by a spark, the spark of the so-called (but misnamed) "extra-current." If we short-circuit the coil, its current—unless there is an electromotive-force to keep it up—will be stopped in a fraction of a second by the internal quasi-friction which we commonly call the "resistance" of the wire.

Now in the armature, when at work, half the current flows—in the standard case we have chosen for consideration—up the coils on the left-hand half of the ring, and the other half of the current flows also up the coils on the right-hand half. If the positive brush is at or near the top, as in Fig. 68, the current flows from left to right through the sections X and W on the left of the brush, and from right to left through the sections T and U on the right of the brush. Now as the armature turns the bars of the commutator come successively into contact with the brush. In Fig. 68 the bars *c* and *d* have already passed the brush; *e* is just leaving it, and *f* is just beginning to pass under it. For a brief moment the brush rests on two adjacent bars *e* and *f*, and thus short-circuits the section V for an instant. The duration will obviously depend on the speed of rotation, on the breadth of the insulating gap between the commutator bars, and on the breadth of the contact-surface of the brush. Now the section V a moment previously belonged to the left-hand half of the ring, and when it has passed the brush, that is to say, when *e* ceases to touch the brush, it will belong to the right-hand half of the ring. It is clear then that in the act of passing the brush the current that was flowing in the section V will be stopped and then started again in the opposite direction through its coils. Every section of the armature as it passes the brush will similarly be transferred from one half of the ring to the other, and will have its current reversed. This is in fact the act of commutation. Now suppose it were arranged that the act of commutation should occur exactly at the point when the coils of the section are not cutting any magnetic lines whatsoever: so that while the coil is short-circuited it shall not be the seat of any induced electromotive-force. Then the current in it will die out, and as it emerges from under the brush it will be thrown as a perfectly idle coil upon the right-hand half of the ring, in which a current is flowing toward the brush. Just before the bar *e*

FIG. 68.



THE ACT OF COMMUTATION OF A SECTION OF THE ARMATURE OF A GENERATOR.

parts company from the brush, the current coming up through T and U is flowing through *e* to the brush: but as *e* moves away this current has suddenly to go also round the coils of V. But the current cannot instantly rise to its full strength in the idle coil V, hence before V really gets to work, the current sparks across between *e* and the brush. We have here supposed V to be a perfectly idle coil: now suppose that it is not idle but is actually still cutting magnetic lines, as would be the case if the brush instead of being shifted forward to the neutral line *n n'* had been further to the left. Then it is clear that during the moment of short-circuiting there will be an electromotive-force acting in the coil as it passes the brush. Such an electromotive-force, even though small, may produce momentarily a large current, because the short-circuited resistance is so small. Hence the sparking will be worse than if the coil were absolutely idle.

Now suppose that the brush is shifted just so far the other way, in the direction of the rotation,[1] that as the coil passes the brush it is beginning to enter the fringe of the magnetic field on the right. In that case it will be beginning to cut the magnetic lines in such a way as to tend to set up a current in the reverse direction through it. The ideal arrangement is attained if the brushes be shifted just so far beyond the point of maximum electromotive-force that while the sections pass under the brush and are short-circuited they should actually have a small reverse electromotive-force induced in them; and this action should last just so long in each successive section as to stop the current that was circulating, and start a current in an opposite direction and let it grow exactly equal in strength to that which is circulating in the other half of the armature, which it is then ready to join. If this set of conditions could be attained there should be *no sparks*. A magnetic field of precisely the proper intensity to cause reversal in the commuted section of the armature can usually be found just outside the tip of the pole-piece, for here the fringe of magnetic lines presents a density which increases very rapidly. Since a more intense field is needed to reverse large currents than is required for small ones, it follows that the angle of lead that must be given to the brushes will be slightly greater for large currents than for small ones.

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[1] In the case of a motor, which is separately considered in Chap. XX., the brushes must be shifted in the *opposite* direction to the rotation; *i. e.* there must be a negative lead.

If the brushes are not rocked sufficiently far forward as to touch at the neutral points, there will be free sparking. If they are shifted beyond the neutral points, the sparking is in general less. That is to say there is usually much sparking when the lead is too little; a little sparking when the lead is too great; and no sparking when the lead is right. When the lead is greater than is necessary there is a waste of energy due to the generation in the short-circuited coil of a larger reverse current than is necessary. Moreover, as the lead is increased beyond the neutral point, all the coils that lie in the region between the neutral point and the diameter of commutation are exerting counter electromotive-forces, and the potential at the brushes falls from its maximum.

If in a badly-designed dynamo the armature current circulation in any section is very great, and the field-magnet very weak, it may happen that no position can be found[1] for the brushes in which the intensity of the field is sufficient to reverse the current in the section. Such a dynamo will spark incurably. It is evident that sparklessness will be promoted (1) by dividing up the armature into many sections, so that the reversals of the currents may be done in detail; (2) by making the field-magnet a relatively powerful one; (3) by so shaping the pole-surfaces as to give a suitable fringe of magnetic field of graduated intensity; (4) by choosing brushes of suitable thickness, and keeping their contact-surfaces well trimmed. (See also Chapter XVI.)

Besides the cause of ordinary sparking explained above there are some causes of an exceptional nature. In those dynamos (chiefly those used in arc-lighting) that are constructed to work at high potentials approaching or exceeding 1000 volts there sometimes occurs a phenomenon known as "flashing-over." A long blue spark will on a sudden alteration of the resistance of the circuit be drawn out around the circumference of the commutator from brush to brush. This spark, which is more of the nature of an arc, does little harm in the case of those dynamos which are constructed with commutators of few parts separated by air-gaps, but is very harmful in the case of dynamos having commutators of the ordinary sort with thin mica insulation between the bars; for these are easily short-circuited by the flash-over.

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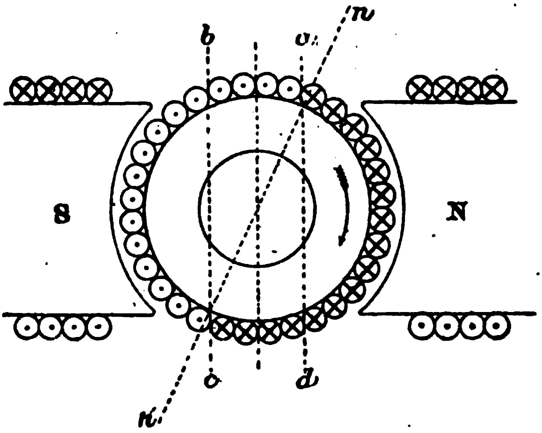
[1] I have seen a dynamo in which the armature overpowered the field-magnets. When the brushes had a small lead there was a good electromotive-force, but it sparked excessively. With a large lead of nearly 90° the sparks disappeared, but the electromotive-force also vanished!

Another cause of sparking is want of symmetry in the winding of the armature: some of the older forms of the Siemens armature were defective in this respect. If the coils of one half of the armature are either more numerous or *nearer to the iron core*, on the average, than those of the other half, the two induced electromotive-forces in the two halves of the armature will be unequal, and, consequently, at every revolution, the neutral points will shift first forward, then backward, giving rise to sparks. Jumping of the brushes when the collector is untrue, or when the brush-holders are defective, is another prolific cause of sparking.

Formerly the fact that a lead must be given to the brushes was ascribed to a sluggishness in the demagnetization of the iron of the armature, and even now some authorities take the view that part of the displacement of the magnetism in the armature is due to the sluggishness of demagnetization of the iron. On the other hand no experimental proof has ever yet been given that the displacement is due to a true magnetic lag. Ewing has shown (see p. 165) that there is a *slow* creeping up of magnetism under the influence of protracted magnetizing forces: but such "viscous hysteresis" will not account for the necessity of giving a lead to the brushes. The apparent magnetic sluggishness of thick masses of iron is demonstrably due to internal induced currents; and for this very reason no one uses solid iron in armature cores. Neither has it been shown that thin iron plates or wires, such as are used in armature cores, are slower in demagnetizing than magnetizing. Indeed, the reverse is probably true; and until further experimental evidence is forthcoming, it will be assumed that the alleged magnetic lag is negligibly small in its effects. For further discussion of this, see some experiments which were described in Appendix V. of the third edition of this work. The generation of eddy-currents in any part of the revolving armature will necessarily be accompanied by a demagnetizing action, and will also affect the lead.

Demagnetizing Action of Armature.—If in a dynamo there is a forward lead given to the brushes for the purpose of stopping the sparking, there at once results another reaction, namely the production of an actual demagnetizing force or "back-induction." That the armature current does so act is readily demonstrated by considering Fig. 69. Here the field-magnet and armature are represented as before, but the brushes have been given a forward or positive lead; the neutral line *n n'* lying obliquely. The currents are flowing towards the observer in the armature conductors on the left of the neutral line, and from the observer in those on the right of that line. Now let the two lines *a b*, and *c d*, be drawn

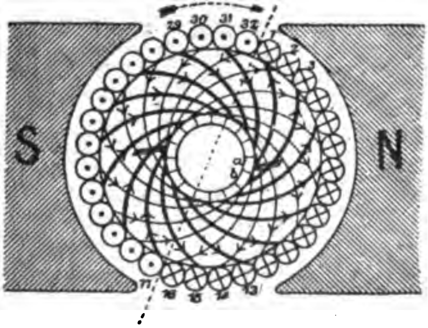
Fig. 69.



Demagnetizing Action of Armature Current of Generator.

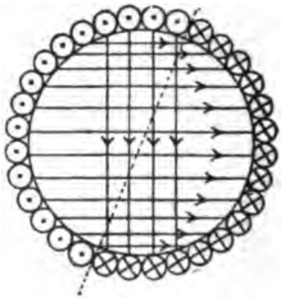
squarely across the armature through the points of commutation corresponding to the two brushes. These lines intersect the outline of the armature in four points. In the diagram there are thirty-two conductors spaced out around the core disk of the armature; and as this armature is drum-wound the end connexions of the conductors will probably be somewhat like those shown in Fig. 70, where each conductor is connected across the end by a double-curved connector to the conductor that is next to the one diametrically opposite.[1] Now so far as any magnetizing actions are concerned it does not matter what the end connexions are, provided they are compatible with the flow of current indicated above in Fig. 69, with current advancing along the sixteen conductors on the left of $n\,n'$ and retreating along the sixteen on the right of $n\,n'$. Hence we may consider them, temporarily, as grouped in any way that will assist us to understand their action. Suppose then that the four conductors from 29 to 32 are joined across the ends[2] to the four from 13 to 16; and let the twelve conductors from 1 to 12 be joined across to the twelve from 17 to 28. Our armature windings are now distributed into two belts, one horizontal belt of twelve windings which

Fig. 70.



Actual Connexions at end of Drum-windings.

Fig. 71.



Conductors Grouped into Cross-magnetizing and Demagnetizing Belts.

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[1] For modes of connecting drum-windings, see Chapter XIII.

[2] See Swinburne in *Journal Soc. Teleg. Engineers*, xv. 542, 1886.

tends simply to *cross-magnetize*, and one vertical belt of four windings which tends simply to *demagnetize*; for it will be seen that the direction of the circulation around the vertical belt is opposite to the direction of the circulation of current in the magnetizing windings. The breadth of the belt of demagnetizing windings is obviously proportional to the angle of lead, since it subtends double that angle. If the armature in question were carrying 100 amperes then, since there are two paths through the armature circuit (p. 64) each conductor must carry 50 amperes. Hence the number of ampere-turns of cross-magnetizing force is $50 \times 12 = 600$; and the number of ampere-turns of demagnetizing force is $50 \times 4 = 200$.

Now the cross-magnetizing action which, as we have seen, distorts the field, does of itself slightly diminish the flux of magnetic lines that crosses the armature core from side to side, because in the oblique resultant direction of the magnetization the increased flux tends to produce greater saturation. For other researches on the effect of a cross-magnetism in diminishing the magnetism of the core, see papers by Siemens[1] and Schültze[2] in *Wiedemann's Annalen*. Schültze, in the course of twenty-four experiments, found that the cross-magnetization of an iron core always diminished the longitudinal magnetization. The most recent experiments of these effects are those of Kennelly.[3]

Frölich, in certain experiments with an old-type Siemens dynamo, found that the reaction of the armature current diminished the effective magnetism of the field-magnets nearly 25 per cent. In a more recent research Strömberg,[4] using a Schuckert dynamo, measured the demagnetizing effect of the armature current, and expressed it as being equivalent to a certain number of negative ampere-turns. When the exciting power of the current in the field-magnet coils was maintained at 6250 ampere-turns, the demagnetizing effect of the armature current was as follows:—

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[1] Werner Siemens. *Wiedemann's Annalen*, xiv. 634, 1882.

[2] Schültze. *Wied. Ann.*, xxiv. 663, 1885. See also Oberbeck, Habilitations-Schrift, 1878.

[3] *Electrician*, xxv. 111, 1890.

[4] *Centralblatt für Elektrotechnik*, p. 283, 1887.

Armature Current.	*Equivalent Negative Ampere-turns.*
7·4	650
12·0	850
25·4	1450
44·0	2450
60·4	3650

With stronger constant excitation of the field-magnets the demagnetizing effect of the armature currents was greater. With 13,400 ampere-turns, the demagnetizing effect of sixty amperes in the armature was equivalent to 4400 ampere-turns. With 25,200 ampere-turns the demagnetizing effect of only 30·5 amperes was equivalent to 3100 ampere-turns. This unexpected effect may probably arise from the iron of the field-magnet arriving earlier at a higher stage of saturation than the armature core. It may also have been dependent on the positions of the brushes, which is not specified by Strömberg. In a Manchester dynamo, tested by Prof. Ayrton,[1] 5846 ampere-turns of magnetizing power were needed when no lamps were on, and 10,000 when the machine was furnishing its full output of current: of the additional 4154 ampere-turns, 1754 were needed to compensate for the lost volts (due to internal resistance and lessened permeability) and 2400 to compensate for the demagnetizing effect of the armature current with the increased lead needed to prevent sparking. The greater the lead given to the brushes in a dynamo used as a generator, the greater is the demagnetizing effect of the armature current. In motors, since for a right-handed rotation in a right-handed field, the direction of the armature current is opposite to that in the dynamo, a negative or backward lead has to be given to the brush to avoid sparking—and this backward lead also results in a demagnetizing tendency. If a negative lead (*i. e.* a displacement from the neutral line in the opposite direction to the sense of the rotation) is given to the brushes of a generator, the magnetizing effect of the armature currents will tend to assist the magnetization of the core. Drs. J. and E. Hopkinson[2] have even shown that with a backward lead a dynamo can excite itself by means of the armature currents only; but in such cases of negative lead there is a destructive amount of sparking. The demagnetizing effect is of course proportional to the number of effective ampere-turns of the armature circuit that surround the magnetic circuit, and therefore to the actual number of ampere-turns included, as we have seen, in a belt of double the angular breadth of the angle of lead.[1] Several expedients have been proposed to compensate the cross-magnetizing tendency of the armature currents, and so obviate the variations of lead. In one due to Mather,[2] a small bar electromagnet excited by the armature current is placed perpendicularly between the pole-pieces. Swinburne[3] has discussed the advantages of various similar arrangements for this purpose. Professor E. Thomson proposes to place a series coil on a movable frame over the armature and tilt it till it brings back the neutral point.

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[1] *Journal Inst. Electrical Engineers*, xix. 175, 1890.

[2] *Phil. Trans.*, 1886, part i. p. 347.

In relation to the interference of the armature with the magnetization of field-magnets, it may be pointed out that the "characteristic" curves of dynamo machines (see Chap. X.), which are used to show the rise of the electromotive-force of the machine in relation to the corresponding strength of the current, are sometimes assumed, though not quite rightly, to represent the rise of magnetization of the field-magnets. They represent rather the magnetization through the armature. Now, though the magnetization of an electromagnet may attain to practical saturation, it does not, under a still more powerful current, show a diminished magnetization. But the characteristics of nearly all series-wound dynamos show—at least for high speeds—a decided tendency to turn down after attaining a maximum; and in some machines, for example the older form of Brush with cast-iron ring (see Fig. 157), this reaction is very marked. The electromotive-force diminishes, but the magnetism of the field-magnets does not. An explanation of this dip in the characteristic was put forward by Dr. Hopkinson, in his lecture on "Electric Lighting," before the Institution of Civil Engineers, April, 1883, attributing this to the reaction of self-induction and mutual induction between the sections of the armature. No doubt this cause contributes to the effect, as all such reactions diminish the effective electromotive-force. Part of the effect is due to the distortion of the magnetism, but most to the demagnetizing effect as the lead of the brushes is increased. It is at least significant that in the older form of Brush machine, where the reduction of electromotive-force is very great, there is also such a mass of iron in the armature, and so variable a lead at the brushes. Machines with descending characteristics are preferred for arc lighting.

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[1] According to Peukert, who, however, does not specify the angle of lead, the demagnetizing effect of the armature current is proportional to the 1·3 power of the armature current. See *Centralblatt für Elektrotechnik*, ix. 484, 1887.

[2] See *La Lumière Electrique*, xix. 404, 1885.

[3] *Journal Inst. Electrical Engineers*, xix. 105, 1890.

The question of lead of brushes, sparking, and field necessary to reverse the current in a section is further considered in Chapter XVI. in relation to the design of dynamos and the load (or ampere-turns) which an armature can carry.

Spurious Resistance.—There is yet another effect which results from the existence of self-induction in the coils of the armature. In each section the current tends to go on, and in fact does actually go on for a brief time after the brush has been reached. Then the energy of the current in that section is wasted in heating the copper wire during the interval when it is short-circuited; and as it passes on, energy must again be spent in starting a current in it in the inverse direction. All these reactions are of course detrimental to the output of current by the dynamo: especially the loss in short-circuiting. It has been shown by M. Joubert[1] that the loss of energy due to the reversals of the current in the sections of a ring armature is equal to $\frac{n\,L\,i_a^2}{4}$ per second, where n is the number of revolutions per second, L the coefficient of self-induction for the entire ring, and i_a the armature current. Professors Ayrton and Perry have very aptly pointed out[1] that the matter may be conveniently expressed in another way. Since the energy per second conveyed by a current running through a resistance r is equal to $r\,i^2$, it is evident that the energy lost per second by self-induction is the same as if there were an additional resistance[2] in the armature of the value $r = \frac{n\,L}{4}$.

---

[1] *Comptes Rendus*, June 23, 1880, January 9, 1882, March 5, 1883; and *L'Electricien*, April, 1883. The proof of the above expression is simple. Electric work per second is expressed as product of volts and current. If N magnetic lines are cut n times per second, the average rate is n N. If a ring circuit has coefficient of self-induction L, then current $\frac{1}{2}\, i_a$ on being sent through that circuit will create $\frac{1}{2}\, \mathrm{L}\, i_a$ lines of force. Hence the current $\frac{1}{2}\, i_a$ is virtually caused n times per second to cut across $\frac{1}{2}\, \mathrm{L}\, i_a$ lines of force; or the work done in stopping the half armature current in all the sections one after the other for a second of time is $\frac{1}{4}\, n\, \mathrm{L}\, i_a^2$.

There is, therefore, in a rotating armature, an *apparent* increase of resistance proportional to the speed, and this apparent increase, due to self-induction, cannot be got rid of by subdividing the armature into a larger number of sections. It can be diminished in degree by using in the armature more iron and fewer turns of wire, in other words by diminishing the magnetic moment of the coil while giving the field-magnet an increased advantage. The existence of an apparent resistance varying with the speed was first pointed out by M. Cabanellas.[3]

Eddy-Currents.—There are two other inductive reactions in the armature to be considered. If any of the framework or metal supports that carry the armature constitute closed circuits which can cut the magnetic lines, they will be the seat of wasteful currents, which will eddy round in them, heating them and absorbing power. In the iron of the armature cores, if not properly laminated, internal eddy-currents (the so-called "Foucault currents") may be set up, absorbing energy and producing detrimental heat; and such currents will also be produced within the conductors which form the coil of the armature, if these are massive as in the "bar-armatures" used for machines that have a large output of current. Frölich, in 1880,[1] pointed out the effect of the presence of these currents; and to them he attributed not only the otherwise unexplained deficit in the work transmitted electrically by a generator to a motor, but also the diminution in the effective magnetism (discussed above as a result of cross-magnetism, and found by Frölich to amount to 25 per cent. of the whole magnetism) observed with great currents and high speeds; and further he attributed to this cause the apparent increase in the number of "dead-turns"[2] at high speeds. Doubtless such currents exist, and the energy they waste will be nearly proportional to the square of the speed:[3] but they may be indefinitely diminished by proper lamination, insulation, and disposition of the structures of the armature.

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[1] *Journal. Soc. Teleg. Eng. and Electr.*, xii. No. 49, 1883.

[2] The value here assigned depends on the assumption that during the moment of short-circuiting the current in the section simply dies out. If it is stopped and reversed by the introduction of a counter electromotive-force, as it ought to be, the value will be less.

[3] *Comptes Rendus*, January 9, 1882, and Nov. 24, 1884; see also Picou, *Manuel d'Electrometrie*, p. 123; and Lodge in *Electrician*, July 31, 1885.

Lamination.—The rules for the proper lamination of structure are different in the different parts; for in the armature core it is desired to cut off all circulation of current that might be induced parallel to the armature conductor; and in the armature conductors it is desired to cut off all flow of current from one side or edge of the conductor to the other. The planes of lamination must of course be arranged to cut right across the direction in which the parasitic current might otherwise flow. Now since (see p. 22) the direction of the induced electromotive-force, the direction of the motion, and the direction of the magnetic lines are all three at right angles to one another, it suffices in each case to describe the plane of lamination, by stating to which of these three directions it must be normal. It will then contain, or be parallel to, the other two directions.

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[1] Berlin Academy, *Berichte*, Nov. 18, 1880; and *Elektrotechnische Zeitschrift*, ii. 174, May, 1881; also vol. ix., Nov. and Dec., 1888.

[2] Meaning the number of revolutions by which the actual speed exceeds the number needed, in the absence of all reactions, to produce the electromotive-force.

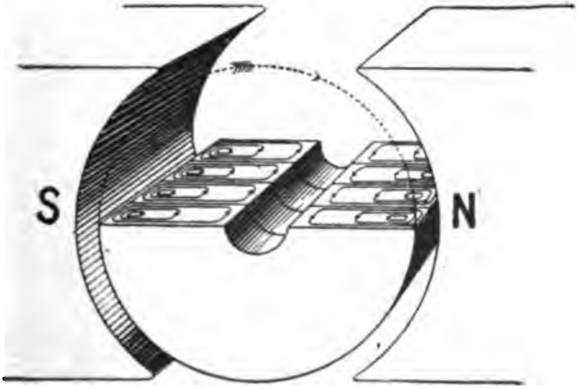
[3] Clausius has introduced terms into his equations (*Wied. Ann.*, xx. 354, 1883; and *Phil. Mag.*, series 5, xvii. 46 and 119, 1883) to include the effects of the eddy-currents. They have also been theoretically treated by H. Lorberg (*Wied. Ann.*, xx. p. 389, 1887).

Direction of	Direction of Lamination Planes.		
	In Armature Cores.	In Armature Conductors.	In Polar Masses.
Motion.	parallel	normal	parallel
Magnetic Lines.	parallel	parallel	parallel
Induced Electromotive-force.	normal	parallel	normal

It will be noticed that the lamination for the polar masses is the same as for the core; so that the polar masses are virtually continuations of the core-disks.

The necessity for dividing the cores of drum armatures and of ring armatures (if cylindrical, not discoidal) into core-disks, may be illustrated as follows :—In any conductor rising in the left-hand gap-space there will be generated an electromotive-force tending from back to front. Hence if the core were of solid iron, a current would flow forwards along the outer part of the core on the left, and back along the outer surface on the right. Division of the core into disks will obviously minimize such currents. It will not, however, entirely eliminate them, for as Fig. 72 shows in the sectional view of the core-disks, it is possible for eddy-currents to flow in the substance of these. As a matter of fact it is found

FIG. 72.



EDDY-CURRENTS IN CORE-DISKS.

that if they are too thick, or are not properly insulated from one another, they heat: and the heating is mainly at the outer surface, where the eddies are strongest. As a general rule it may be said that core-disks should not exceed 2 millimetres in thickness. The same thickness is suitable for the ribbon cores of discoidal rings. The new laminated armature of the Brush arc-light machine, Fig. 303, p. 462, when used in place of the old solid armature, Fig. 302, was found to diminish greatly the number of "dead turns," besides saving much energy previously lost in heating.

With ring armatures that have an internal field (see p. 76) similar eddies will be set up in the driving spindle and in the metal arms that support the core; wasting power and heating them.

If there is a stray magnetic field leaking from the flanks of the polar masses into the flat surface of the end-disks of the core, eddy-currents will also be set up in the latter. This can be obviated by making the total axial length of the armature core rather greater than the length of the polar masses parallel to the axis.

Eddy-currents in Pole-pieces.—If the masses of iron in the armature are so disposed that as it rotates, the distribution of the lines of force in the narrow field between the armature and the pole-piece is being continually altered, then, even though the total amount of magnetism of the field-magnet remains unchanged, eddy-currents will be set up in the pole-piece and will heat it. This is shown by Figs. 73 to 78, which represent the effect of a projecting tooth, such as that of a Pacinotti ring, in changing the distribution of the magnetism of the pole-piece. Figs. 76 and 77 (corresponding respectively to Figs. 74 and 75) show the eddy-currents, grouped in pairs of vortices. The strongest current flows between the vortices and is situated just below the projecting tooth, where the magnetism is most intense; it moves onward following the tooth. Fig. 78 shows what occurs during the final retreat of the tooth from the pole-piece. These eddy-currents penetrate into the interior of the iron, although to no great depth. Clearly the greatest amount of such eddy-currents will be generated at that part of the pole-piece where the magnetic perturbations are greatest and most sudden. A glance at Figs. 63, 67, 77, and 78 will at once tell us that this should be at the "leading" corner or "horn" of the pole-piece of the generating dynamo. As a matter of fact, when any dynamo which has horned pole-pieces (such as the Gramme) has been running for some time as a generator this is found to be the case. The "leading" horns *a* and *c*, of Fig. 79, are found to be hot, whilst the "trailing" horns *b* and *d* are found to be

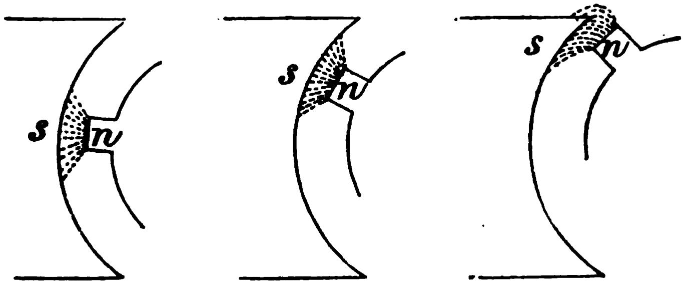


FIG. 73. FIG. 74. FIG. 75.

ALTERATION OF MAGNETIC FIELD DUE TO MOVEMENT OF MASS OF IRON IN ARMATURE.

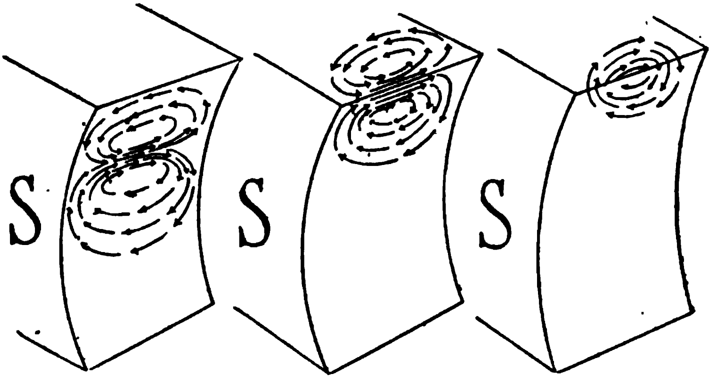


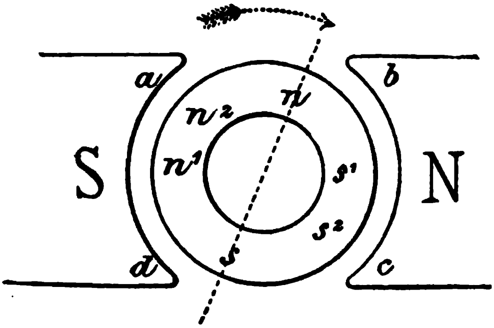
FIG. 76. FIG. 77. FIG. 78.

EDDY-CURRENTS INDUCED IN POLE-PIECES BY MOVEMENT OF MASSES OF IRON.

comparatively cool. When the dynamo is used as a motor, the reverse is found to be the case: the "leading" horns *a* and *c* are cool, the "trailing" horns *b* and *d* are hot. A reference to the magnetic field of the motor, as drawn in Chap. XX., will explain the latter case.

Closely connected with this effect is another, first pointed out to the author by M. Cabanellas. A Gramme magneto machine with permanent magnets is observed to lose power during its use as a motor; the field-magnets decrease in strength. If, then, it is used as a generator, the field-magnets regain their magnetism. The effect is explicable[1] when the

FIG. 79.



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[1] The following explanation was given by the author at the International Conference of Electricians at Philadelphia, 1884 (see report in *Electrical Review*, Dec. 13, 1884). "To explain these facts, and their mutual relation, I must relate one other observation which I have made, and which connects both sets of facts. . . . . Suppose you take a horse-shoe magnet, having the usual armature or "keeper" of iron. You can purchase such an instrument of any optician, who will probably give you instructions never to pull the armature off suddenly for fear you injure the magnetism. He could not possibly give you worse directions. Take such a magnet and try what the effect really is. Fasten it down upon a board with brass screws, and fix a magnetometer near it—a common compass will answer—and notice how much the magnet pulls the needle round. Then put on the armature, by placing it at the bend of the magnet; draw it slowly to its usual position, and suddenly drag it off. You will find that by this action your magnet will have grown stronger. Do this twenty times, and you will make it considerably stronger. I have made a magnet 1·2 per cent. stronger by putting on the armature very gently and pulling it off suddenly. If you reverse the operation, by letting the armature slam suddenly against the poles and then detach-

magnetizing effect of the eddy-currents is taken into consideration.

Effects of Mutual Induction.—Some forms of armature are peculiarly defective in the matter of being so constructed as to allow of much induction between neighbouring sections or parts of the coil, causing the rise of the current in one section to exert an opposing induction on a neighbouring section, and thereby, though not necessarily wasting any energy, making the machine act as if it were a smaller machine. The Bürgin armature, which had six or eight rings side by side on one spindle, suffered from induction between each section, and those belonging to the rings on the right and left of it; and it was only by a careful alternation of positions that this defect was mitigated. In disk armatures of the Niaudet and Wallace-Farmer type each of the parallel coils acted inductively on its neighbour. Beyond doubt the armature with least of this defect is the drum armature.

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ing it gently, you will find that the magnetism will go down. I have made magnets lose 1·3 to 2·1 per cent. in this way. Why does this occur? How does it explain the two phenomena noticed just now? If you suddenly take away a piece of iron from a magnet, you do work against the magnetic attraction, and the induced currents which are set up in the iron or steel of the magnet are always (as we know from Lenz's Law) in such a direction as to oppose the motion; that is to say, they are in such a direction as will make the magnet pull more strongly than before. By suddenly detaching the armature, we magnetize the magnet more strongly than before, by means of currents circulating within its own mass and within the mass of the armature. In the reverse motion, when you allow the armature to slam up, there are induced currents which are in such a direction as to oppose the motion of slamming; they, therefore, decrease the magnetism of the magnet. Apply this to the dynamo and to the motor. You magnetize more highly by pulling off the armature. That is precisely what is occurring in the field when the machine is being used as a generator. You are dragging away the armature from the active horn *a* of the pole-piece, and the effect is to generate induced currents in that horn. It therefore gets hot. So does the other leading horn *c*, for the very same reason. In the case of the motor the horns *b* and *d* are the active ones, and the armature is being continually dragged up toward them, and they get hot from internally induced currents. It is for this reason that in my Cantor Lectures I recommended that pole-pieces should always be laminated. The presence of these induced currents explains the heating effect, and it also explains how it is that when a magneto machine is used as a motor the magnet is weakened, and when used as a generator the magnet is strengthened."

Clausius has shown[1] that after a section has been short-circuited on passing a brush, it exercises a deleterious inductive effect on the neighbouring coil in advance of it, and that this effect is proportional to the number of turns in the section. It can, therefore, be diminished by increasing the number of sections, thereby diminishing the number of turns of wire in any one section of the armature.

Mutual induction between adjacent parts is of enormous importance in alternate-current machines; and indeed everywhere, throughout dynamos in general.

Lag due to Self-Induction.—This electric inertia of the current which circulates in the sections affects slightly the lead that must be given to the brushes, and it also reacts on the neighbouring coils. If a coil is short-circuited too early, before it reaches the neutral point, the sudden rush of its own current round itself tends by mutual induction to stop the current in the coil behind it, and to accelerate the inverse current in the coil in front of it. These actions are diminished by increasing the number of sections and making the individual sections consequently smaller. The induction even extends to the iron of the cores. In every particle of the iron at the moment when it arrives at the position where its magnetism must be reversed, an internal current is set up which retards the reversal of the magnetism and makes it *apparently* lag in its magnetization, as well as grow hot. This effect can also be diminished by properly laminating the core and arranging it so that its magnetism is reversed gradually instead of suddenly.

Remedy for Induction Troubles.—The one important way of diminishing these deleterious reactions is happily a very simple one. It is clear that the demagnetizing effect is due to the lead of the brushes, and this again is due to the cross-magnetizing action. This therefore must be compensated or reduced to a minimum by some means. It has been shown that the electromotive-force of the dynamo is proportional to three things, the number n of revolutions per second, the total number **N** of magnetic lines in the effective field, and the number C of conductors around the armature. Now, for a given size of armature, the inductive reactions are proportional to C. If we can decrease C while increasing either of the other terms, we may thereby decrease the deleterious reactions and yet keep the same electromotive-force as before. Now it is inconvenient to increase the speed, and moreover some of the deleterious reactions, mechanical (such as friction) as well as electrical, increase when the speed increases. The only way then is to increase **N**, the number of magnetic lines in the effective magnetic field. This can be done by having enormously strong field-magnets which will entirely overmaster the armature. If the field-magnets are large, and of wrought iron, and if there is plenty of iron in the armature core, then, without increasing the speed, we may get the same electromotive-force while using fewer turns of wire on the armature. The ideal dynamo of the future for constant pressure work will have but one turn of wire to each section. It will have practically no lead at the brushes, will not spark, and its internal resistance will be practically *nil.*

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[1] *Wiedemann's Annalen*, Nov. and Dec., 1883; and *Phil. Mag.*, Jan. and Feb., 1884.

It is also important to observe that distortion of the magnetic field and some of the resulting troubles can be partially obviated by so shaping the polar surfaces that they come nearer to the armature at the region at right angles to the diameter of commutation; the pole-pieces being cut away so as to give a wider clearance at the outer edges. It is obviously possible by proper shaping to produce concentration of the magnetic lines at any desired region of the magnetic field. Ryan[1] has made a special study of the relation between the polar shape, the breadth of the gap-space, and the resulting curve of induced electromotive-force.

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[1] *Amer. Inst. Electrical Engineers*, Sept. 22, 1891.

CHAPTER V.

MECHANICAL ACTIONS AND REACTIONS IN THE ARMATURE.

WHENEVER a conductor carrying an electric current lies in a magnetic field across the direction of the magnetic lines, it experiences a mechanical force. This force always tends to drag the conductor sideways out of the field, and acts in a direction at right angles to the magnetic lines and at right angles to the conductor itself. Rules for remembering the relation between the directions of the magnetic lines, the current, and the resulting force, have been given by various writers. The most convenient rule is that of Fleming, in which the three directions are represented respectively by the fore-finger, the middle-finger, and the thumb of the *left* hand.[1] In a motor it is this drag on the conductors which drives the armature mechanically. In a dynamo the drag acts against the driving power of the steam-engine and opposes the rotation. When a mechanical engineer first considers a dynamo he is often puzzled to understand what there is in it that necessitates so much driving power. He sees the armature revolving with ample clearance between the polar faces of the field-magnet. The friction of the bearings does not absorb more than a minute fraction of the horse-power delivered by the engine. He sees the brushes pressing against the copper commutator, but knows that their friction is also a negligible quantity; moreover he is soon informed that friction has nothing to do with the operation of the machine. Where does the power go to? What is it that requires such a force to be continually exerted to keep up the rotation? The answer is, that there is a continual drag of the invisible magnetic lines on the conductors through which the current is flowing: that the generation of the current depends on the conductors being forced across the field that drags at it. In every form of apparatus generating currents by magneto-electric induction, the currents generated produce a mechanical reaction tending to stop the very motion that generates them.

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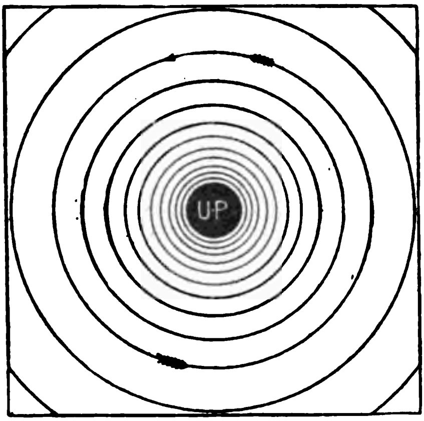
[1] Contrast with p. 23, where, for the current generated in *a dynamo* the *right* hand is used. Remember that in a dynamo the direction of the current agrees with that of the induced electromotive-force, whereas in a motor the current flows against the induced electromotive-force. Further, in the dynamo the mechanical drag acts against the direction of motion, whereas in a motor the drag produces the motion in the same direction as itself, Hence the use of *right* hand for dynamo, *left* hand for motor, to give the relation between magnetism, current, and motion.

The drag of a magnetic field upon a conductor that carries a current may be considered from the magnetic point of view. As pointed out on p. 26, above, such a conductor is surrounded by a whirl of magnetic lines. Around a long straight conducting wire not placed in any magnetic field, these magnetic lines form a system of concentric circles (see Fig. 13, p. 27) which are close together near the conductor, and wider apart at a distance away, resembling Fig. 80 in general disposition.

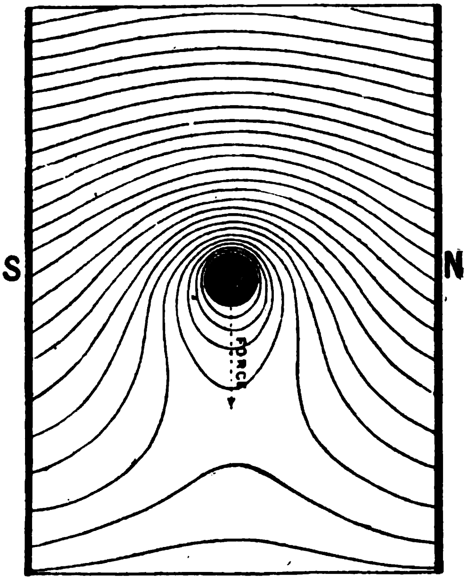
Fig. 80.



Magnetic Field of a Straight Conductor carrying a Current.

If the current is coming towards the observer, or *up*, in the figure which shows a cross-section of the conductor, the positive direction along the magnetic lines will be left-handed or counter-clock-wise. If now such a conductor be placed in a uniform magnetic field—one, for example, between a large north magnetic pole on the right and a south magnetic pole on the left; a compound field will be produced, due to the blending of the magnetic lines of the conductor with those of the field. In considering this distorted magnetic field it should be remembered that the mechanical actions that result may always be known by supposing the magnetic lines to act as elastic cords tending to shorten themselves. There is in fact a tension along the magnetic lines and a pressure at right angles to them, both proportional at every point to the square of their density. A mere inspection of the lines of Fig. 81 will accordingly show that there will be a resultant drag upon the conductor in the direction shown by the dotted arrow.

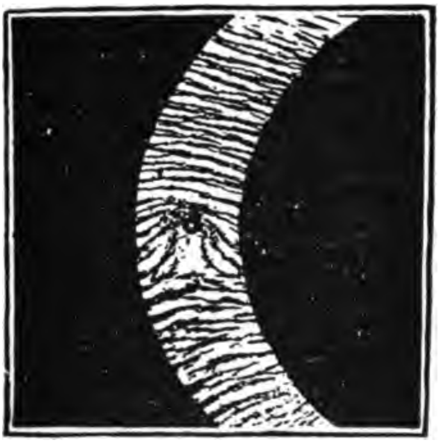
FIG. 81.



MAGNETIC LINES DUE TO CONDUCTOR CARRYING CURRENT PLACED IN MAGNETIC FIELD.

The actual magnetic field produced around a conducting wire in a magnetic gap between two poles, as revealed by iron filings, is shown in Fig. 82.

FIG. 82.



ACTUAL MAGNETIC FIELD AROUND CONDUCTING WIRE IN MAGNETIC GAP.

We may consider Fig. 82 as approximately representing that which goes on in a dynamo, or in a motor, in each of the gap-spaces between the armature core and the adjacent polar face. Each conductor on the armature will be similarly dragged by a force proportional to the intensity of the magnetic field and to the strength of the current.

Torque and Speed.—Engineers recognize that power, being the rate of expending energy or of doing work, can always be expressed as the product of two factors. In the case of rectilinear motion, the power may be expressed as the product of force and speed. For example, if the force pulling along a belt [1] be equal to the weight of 66 pounds, and the belt-speed be 2000 feet per minute, the amount of power it is delivering is 132,000 foot-pounds per minute, or 4 horse-power.

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[1] Or more precisely, the difference between the forces in the tight and slack parts.

But the power may be equally well expressed in terms of angular force (*i. e.* torque) and angular speed; and these quantities are more convenient in the case of power transmitted along a rotating shaft.

The useful term *torque*, now generally accepted by engineers, was originally suggested by Professor James Thomson, then Professor of Mechanical Engineering in the University of Glasgow. It is the same thing as that which has gone by the names of "turning moment," "moment of couple," "axial couple," "angular force," "axial force," in German by that of "Zugkraft," and in French by those of "effort statique," and "couple mécanique." *Torque* is preferable in many ways to any of the older terms. Just as the Newtonian definition of *force* is that which produces or tends to produce motion (along a line), so *torque* may be defined as that which produces or tends to produce *torsion* (around an axis). It is better to use a term which treats this action as a single definite entity than to use terms like "couple" and "moment," which suggest more complex ideas. The single notion of a twist applied to turn a shaft is better than the more complex notion of applying a linear force (or a pair of forces) with a certain leverage.

For torque we shall use the symbol T. If force f acts with leverage (*i. e.* radius) r, the torque is equal to $f \times r$. If the force is in pounds' weight and radius in feet, the torque will be expressed in pound-feet; *i. e.*, in terms of the number of pounds, which, acting with a leverage of one foot, would produce an equal tendency to turn. If force is given in dynes and radius in centimetres, the torque will be expressed in dyne-centimetres. (See Appendix A, on Units.)

In order to bring—

dyne-centimetres	to	gramme-centimetres,	divide by 981
dyne-centimetres	to	metre-kilogrammes,	divide by 981×10^5
dyne-centimetres	to	pound-feet,	divide by $13{\cdot}56 \times 10^6$
pound-feet	to	metre-kilogrammes,	divide by 7·23

Angular speed is commonly expressed by engineers in terms of the number of revolutions per minute, or, sometimes, of revolutions per second. The scientific mode is to express it in *radians per second.* (The radian is that angle whose arc equals the radius; so that 2π radians equal one revolution or 360^0.) The symbol for angular speed is ω, so that if n represents the revolutions per second, $\omega = 2\pi n$.

In order to bring:—

revolutions per minute	to revolutions per second,	divide by 60
revolutions per second	to radians per second,	multiply by 2π
revolutions per minute	to radians per second,	divide by 9·55
radians per second	to revolutions per minute,	multiply by 9·55

We have then the following relations between linear force f, linear speed v, torque T, angular velocity ω, radius r, revolutions per second n, and power w.

$$w = v.f = \frac{v}{r}.fr = \omega \mathrm{T} = 2\pi n \mathrm{T}.$$

The power w will be expressed in *ergs per second*, if v is given in centimetres per second and f in dynes; or if T is given in dyne-centimetres. If T is in pound-feet, w will be expressed in foot-pounds per second.

In order to bring:—

ergs per second	to watts,	divide by 10^7
ergs per second	to kilogramme-metres per second,	divide by $9·81 \times 10^7$
ergs per second	to foot-pounds per second,	divide by $1·356 \times 10^7$
ergs per second	to horse-power,	divide by 746×10^7
watts	to horse-power,	divide by 746
watts	to chevaux-vapeur,	divide by 736
watts	to foot-pounds per second,	divide by 1·356
watts	to kilowatts,	divide by 1000
kilowatts	to horse-power,	multiply by 1·345

Output of Dynamos and Motors.—A good dynamo will convert over 90 per cent. of the mechanical power supplied to it into electric power. Similarly a good motor will convert over 90 per cent. of the electric power supplied to it into mechanical power. Both mechanical power and electric power may be expressed in terms of the same units, either in *horse-power*, or in *watts*, or in *kilowatts*.

Approximate calculations of the horse-power required for a dynamo of any prescribed output are readily made. Multiplying the number of amperes i of current which the dynamo is to yield, by the number of volts e of pressure at which the current is supplied, gives the output in *watts*. Dividing by 746 gives the corresponding electric horse-power, which will be about 90 per cent. of the mechanical horse-power to be supplied to the shaft of the dynamo.

Example : A dynamo is required to furnish 300 amperes (to light 600 glow lamps) at a pressure of 105 volts. Output is 31,500 watts = 42·2 horse-power (electrical). Therefore allow 46·9, or say 50 (mechanical) horse-power.

In the converse way we may calculate the requisite supply of electric power to a motor.

Example : A motor is required to give an actual output of 5 horse-power. Multiplying by 746, we find it must give out 3730 watts as mechanical power ; which will be about 90 per cent. of the electrical power supplied to it. This will therefore need to be about 4144 watts. If the supply is from mains that are at a pressure of 200 volts, the current required will consequently be a little over 21 amperes.

Relation between Torque and Current.—Since the electric power given out by the armature of a dynamo is the product of two factors—volts and amperes—and the mechanical power supplied to it by the rotating shaft is also the product of two factors—speed and torque—it becomes a matter of some interest to ascertain whether there is any direct relation between the factors themselves. Let E stand for the volts generated in the armature, and i_a for the amperes flowing through it. We may then equate the two separate expressions for the number of watts of power supplied to and furnished by that armature as follows :—

$$\text{watts} = \mathrm{E}\, i_a = 2\, \pi\, n\, \mathrm{T} \times 1{\cdot}356\,;$$

where T is given in pound-feet ; n in revolutions per second ; E the whole volts generated by the armature ; and i_a the whole amperes flowing through the armature. But E is proportional to the speed if the magnetism is constant, the fundamental expression for it being (see pp. 47 and 211), for an ordinary two-pole machine,

$$\mathrm{E} = n\,\mathrm{C}\,\mathbf{N} \div 10^8\,;$$

where **C** is the number of conductors around the armature, and **N** the magnetic flux through its core. Inserting this value for E, and cancelling n from both sides, we get:

$$\frac{\mathrm{C}\,\mathbf{N}\,i_a}{1{\cdot}356 \times 10^8} = 2\,\pi\,\mathrm{T}\,;$$

whence

$$\frac{\mathrm{C}\,\mathbf{N}\,i_a}{8{\cdot}52 \times 10^8} = \mathrm{T} \text{ (in pound-feet).*}$$

From this it appears that if in a given machine the magnetism is constant, the torque depends in no wise upon the speed, but only upon the current flowing through the armature, and on the magnetism.

These expressions apply equally to dynamos and to motors. They show that if it is desired to build slow-speed machines provision must be made for a very large magnetic flux; for only by making **N** large can the dynamo at slow speed yield the requisite volts, or the motor exert the needful torque.

Drag on Armature Conductors.—We are now in a position to understand that the drag really comes on the armature conductors. In the dynamo it is they that have to be driven, in the motor it is they that drive. We may at once proceed to calculate the amount of such drag. There are three methods of doing this: two being electrical and one a purely mechanical calculation.

METHOD I.—By the last formula the torque is calculated; and from this the total peripheral force is found by dividing by the known radius of the armature. Hence the force per conductor is obtained by dividing by the number of active conductors.

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* If T is desired in metre-kilogrammes, the divisor on the left must be replaced by the value $61{\cdot}5 \times 10^6$.

Example in the Edison-Hopkinson dynamo (p. 413). $i_a = 326$; $C = 80$; $N = 10{,}850{,}000$; radius $= 0{\cdot}458$ ft.; whence $T = 332$ pound-feet, and total peripheral force $= 724{\cdot}7$ pounds. This would give about 9 pounds average force per conductor if all were active; but only about 58 of them are in the magnetic field at one time; hence, the average force per conductor is about 12½ pounds. If the magnetic field in the gap-spaces is not uniform there comes a stronger drag on those conductors which lie in the place where the magnetic lines are densest.

METHOD II.—The drag on a conductor of length l, in a magnetic field of intensity H, carrying current of i amperes, is

$$f \text{ (dynes)} = i\,l\,\mathrm{H} \div 10.$$

This formula[1] is only applicable if H, the density of the field in the gap-space, is known. If l'' and $\mathrm{H}_{//}$ are given in inch measures (see p. 142), the formula becomes

$$f \text{ (pounds)} = i\,l''\mathrm{H}_{//} \div 11{,}303{,}000.$$

Example, as before: Current in any one conductor will be $\frac{1}{2}\,i_a = 163$ amperes; $l'' = 20''$, and $\mathrm{H}_{//} =$ about 43,300 lines per square inch, the area of the gap-space being about 250 square inches. Whence drag on each conductor $= 12{\cdot}49$ pounds.

METHOD III.—Ascertain actual horse-power on armature; multiply by 33,000 to reduce to foot-pounds per minute, and divide by the peripheral speed (in feet per minute). [The horse-power may be reckoned from the electrical output as on p. 110.] Then divide by the number of active conductors. Or, in symbols,

$$f \text{ (pounds av. drag per conductor)} = \frac{\text{H.P.} \times 33{,}000}{\text{ft. per min.} \times \text{C.}}$$

Example, same as before: Since $i_a = 326$, and $E = 108{\cdot}5$ volts, H.P. $= 326 \times 108{\cdot}5 \div 746 = 47{\cdot}45$. Also periphery $= 2\,\pi \times$ radius $= 2{\cdot}88$ ft. This, at 750 revs. per minute, gives 2158 ft. per min. as peripheral speed. Assuming fifty-eight conductors to be active, we get

$$\text{av. force on each conductor} = \frac{47{\cdot}45 \times 33{,}000}{2158 \times 58} = 12{\cdot}5 \text{ pounds.}$$

A convenient approximate rule may be given as follows:—

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[1] To give f in kilogrammes, the divisor 10 must be replaced by 9,810,000.

If we assume, as a sort of rough average for the magnetic field in the gap-space of a dynamo or motor, the value of 40,000 lines to the square inch, or say 6300 lines per square centimetre, then *the drag per inch of conductor will be* 0·00354 *pound for each ampere of current carried.* In alternate-current dynamos the intensity of the field is seldom more than half as great as this.

Such, then, is the drag that magnetic fields exert upon the armature conductors; and, it must be remembered that the drag is not a steady one. When the conductor emerges from the gap-space, though there is still a current in it, the magnetic drag is taken off. Twice, therefore, in each revolution this drag is suddenly removed and suddenly put on again, increasing the racking action. In the case of alternate-current machines where the relation of phase between the currents and the magnetic fields complicates the matter, the drag is not simply taken off and put on twice in each complete period, but is actually reversed; the armature conductors being driven with a back drag on them, then experience a forward drag and tend to drive, then once more are driven, and again tend to drive as the current reverses. In the alternate current machine acting as generator the intermediate forward drags are slight and of short duration; in the machine acting as motor it is the backward drags that are of short duration.

It must further be remembered that the conductors of the rotating armature are also subject to centrifugal force, and must be strongly held in with external binding-wires to prevent them from flying.

Need of Driving Horns.—It is then obvious that under the mechanical conditions now described there is need of a good positive method of conveying the driving power from the shaft to the conductors on the outside of the armature. In the dynamo it is they, not the core-disks, that need to be driven. In the motor, it is they that drive the shaft. In the design and construction of machines this is a matter of prime importance. The question of construction is complicated by the consideration that whilst the copper conductors must be mechanically connected to the shaft in the most positive way, they must not be metallically connected, but, on the contrary, must be insulated therefrom. Different constructors adopt different modes of accomplishing the end in view. Some makers key on to the shaft a strong hub provided with spokes that project beyond the surface of the core-disks, and, protected by layers of adequate insulation, thus drive the copper conductors. Others secure the core-disks mechanically to the shaft, and insert wedges of wood or of hard fibre into nicks in the periphery to serve as driving horns. In cases where toothed core-disks are used, no other driving horns are necessary, the copper conductors being wound between the teeth. Students of design should carefully examine the practical modes adopted by modern makers described in Chapter XIII.

Curves of Torque.—It was shown above that if the magnetic flux is constant, T was proportional to *i*. But in all cases the current in the armature itself distorts the magnetic field, and, when the brushes are set at a non-sparking point, exerts a demagnetizing action. And, in fact, the magnetism of the machine depends on its mode of winding, whether excited separately, or in series, or in shunt. These matters complicate the relations between T and *i*, and necessitate the use of curves to follow them out.

Frölich has given[1] such curves showing these relations, and has also argued from the law of magnetic saturation that these curves should for small speeds be curved, and for large speeds become nearly straight lines. He has also shown that in a motor the torque is less nearly proportional to the current than in a generator. The following tables summarize the results of his experiments on a series-wound Siemens dynamo used in both functions :—

Generator—							
Current ..	2·83	9·56	14·3	19·8	24·3	36·6	amperes.
Torque ..	5·1	10·61	14·8	21·3	29·6	44·0	kilos.
Motor—							
Current ..	13·3	21·0	28·1	36·8	amperes.		
Torque ..	10	20	30	40	kilos. at circumference.		

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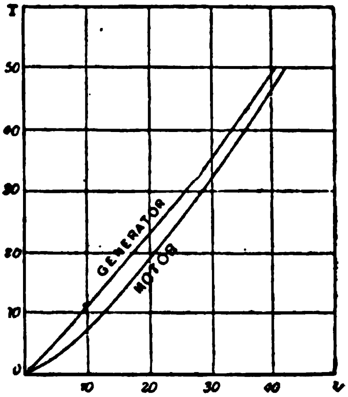
[1] *Elektrotechnische Zeitschrift*, iv. 61, Feb. 1883.

These results are plotted out in Fig. 83 for the two cases. Similar curves have been given by Deprez[1] for the Gramme machine, and by Ayrton and Perry[2] for a De Meritens motor. It can be shown that the torque is proportional to the square root of the heat-waste in the motor or dynamo. As, moreover, the current in a motor cannot be maintained without the continual expenditure of energy equal to $i^2\ r$ watts, it follows that the continuous torque in a motor costs a certain expenditure, which will not only vary with the actual load on the motor, but is different in different types of motor. In a badly designed motor with a weak field-magnet, a strong current running through a high internal resistance (and therefore expending much energy as heat) will produce but a feeble torque. For economy it is therefore important to know at what cost in heat the torque is attained. The ratio may be expressed algebraically as

FIG. 83.



CURVES OF TORQUE.

$$\frac{\mathrm{T}}{\text{heat-waste}} = \frac{\mathrm{E}\, i}{2\,\pi\, n\, i^2\, r} = \frac{\mathrm{E}}{2\,\pi\, n\, i\, r};$$

where r is the internal resistance, E the total electromotive-force of the dynamo, and n the number of revolutions per second. It is, however, preferable to measure T by a direct dynamometric process. Marcel Deprez, who has given to this important ratio the rather awkward name of the "price of the statical effort," has also given curves showing the variation of this ratio with the speed at which the machine is run.

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[1] *La Lumière Electrique*, xi. 42, Jan. 5, 1884.

[2] *Journal Soc. Teleg. Eng. and Electricians*, xii. No. 49, May. 1883. See also Hummel, *Electrotechnische Zeitschrift*, viii. 427, 1887.

Professors Ayrton and Perry have shown, in their memoir on electromotors, that as the speed increases it requires a greater and greater current through the motor to produce a given torque, probably in consequence of the demagnetizing action of eddy-currents.

A number of *mechanical characteristics*, giving the relations between speed and torque in a number of different cases, will be found in Chapter XX, on motors.

Stray Power.—In the preceding paragraphs it has been assumed that the mechanical power applied *at the shaft* to drive the armature was equal to the electrical power actually generated in the armature. The power to be applied at the pulley is, however, always greater than this ; for, in the first place, some of the applied power is lost by friction in the bearings, &c., and never reaches the armature. But of that which actually reaches the armature, not all is actually converted into electrical power. There are, beside the friction at the bearings and brushes, three sources of loss, viz.: (1) air-friction, (2) hysteresis, (3) eddy-currents. The first of these is insignificant, except in those cases where curved spokes are employed with the object of making the armature act as a fan, and even then is small. The second is by no means negligible, but seldom adds more than 1 or 2 per cent. to the driving power. The third is the most important of all, especially in large machines. In all the moving metal masses, unless laminated, there will be eddy-currents set up if they cut magnetic lines. Even in the metal of the shaft, power may be lost from this cause if there is leakage of magnetic lines into it. The mode of investigating the separate sources of loss is described in Chapter XXVIII. on the Testing of Dynamos and Motors. Whatever these losses, it is evident that they all call upon the supply of power: for the power supplied is necessarily equal to the sum of the power actually converted in the armature into electric power, and the stray power wasted in the ways enumerated.

Efficiency of Dynamos and Motors.—Efficiency is a term used in several senses, which it is well to distinguish.

(1) *Efficiency of Conversion* or *Gross Efficiency*, is the

relation between the gross electrical power actually converted in the armature, and the gross mechanical power imparted by belt or coupling to the shaft. If 12 per cent. of the gross mechanical power is lost in friction at the bearings, friction at the brushes, air friction, hysteresis, and eddy-currents then the remaining 88 per cent. being actually converted in the armature, we should describe the efficiency of conversion as 88 per cent.

(2) *Electrical Efficiency*, or *Economic Coefficient*, is the ratio between the nett electric power or nett output of the dynamo, and the gross electric power, or power actually converted in the armature. Thus, if in a shunt dynamo 3 per cent. of the gross electric power is wasted in heating the resistance of the armature, and another 3 per cent. is wasted in maintaining the magnetizing current in the shunt winding, the output or nett electric power will be only 94 per cent. of the gross electric power; or the electrical efficiency is 94 per cent. This ratio depends only on the resistances of the machine. In modern machines it may even attain 97 per cent.

(3) *Commercial Efficiency* or *Nett Efficiency*, is the ratio between the nett electrical output and the gross mechanical power supplied by belt or coupling. It is therefore equal to the product of the efficiency of conversion and the electrical efficiency. In the example given it is 94 per cent. of 88 per cent., or 82·72 per cent.

RELATION OF SIZE TO CAPACITY AND EFFICIENCY.

For years past the author has been the advocate of large dynamos, not because he has any admiration for mere bigness, but because, as in steam-engines, so in dynamos, the larger machines may be made more efficient than the small, in proportion to their cost. There has been a considerable amount of controversy upon the relation that subsists between the linear dimensions of similar machines and their permissible output and their efficiency; the divergence of views arising mainly from difference of opinion as to the assumptions that are suitable at the outset. In the first edition of this work the author laid down the proposition that if the speed of rotation remains the same and the intensity of the magnetic field (per square centimetre) is also maintained unchanged, then the output of a machine n times as great, in all linear dimensions, as any given machine, would be increased in the proportion of n^5, and the coefficient of waste would be in the proportion of n^{-3}. Now though this may be *à priori* true in the abstract, the very assumptions made for the sake of simplification are opposed to actual conditions of working; for it is inexpedient to drive large machines at the same speed as small ones; and to procure equal magnetization with large magnets wastes more energy in proportion, on account of the relatively greater difficulty of getting rid of the waste heat from the magnetizing coils, the energy requisite to be spent on magnetizing being nearly proportional to the volume of iron to be magnetized, and the power of getting rid of the heat being only proportional to the surface. Amongst those who have discussed the problem are Hopkinson, Frölich, Ayrton, Mascart and Joubert, Kapp, Storch, Rechniewski, and Pescetto. According to Hopkinson[1] the capacity of similar machines is proportional to the *cube* of their linear dimensions; the work wasted in magnetizing the field-magnets proportional to the linear dimensions, whilst that wasted in heat in the armature conductors is proportional to the square of the linear dimensions. Mascart and Joubert[2] place the capacity as low as the *square* of the linear dimensions, and draw the conclusion that small machines are preferable to large ones. Pescetto[3] arrives at similar conclusions. Rechniewski[4] follows Hopkinson in assigning n^3 as the proportion. Frölich[5] assigns the value n^4, and criticises the rule of the fifth power given by the author of this work and by Deprez, as involving an increase of n^3 in the current whilst there is an increase of only n^2 in the section of the conducting wires, which further involves that the density of the current in the wires must increase with the size of the machine, which is clearly impracticable. Storch[1] considers constant-current machines to be in a different category from constant-potential machines. Assuming equal intensity of magnetic field, equal peripheral velocity, and equal permissible current-density, he finds that in all machines the ampere-turns requisite for excitation vary as the linear dimensions. For constant-current machines the capacity is proportional to n^3, that is to say to the weight of the machine, or to the volume of copper on the armature. For constant-potential machines he finds the total length of wire on the armature to be independent of the dimensions of the machines; the number of external armature conductors to vary inversely as the linear dimensions; whilst the capacity of the machines is found to vary as n^4, though with undue heating, unless the volume of copper on the armature is also increased as n^4. Storch and Rechniewski agree with Hopkinson that the work lost in field-magnets decreases relatively to that lost in armatures, with an increase in the linear dimensions. On the other hand, increase in the size of the moving masses increases the liability to waste of power by eddy-currents.

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[1] *Proc. Inst. Civil Engineers*, April 1883.

[2] *Leçons sur l'Electricité*, ii. 815, 1886.

[3] *L'Electricien*, xi. 357, 1887.

[4] *La Lumière Electrique*, xxii. 311.

[5] *Die dynamoelektrische Maschine*, p. 168, 1886.

Recent contributions to the discussion come from Mr. Kapp[2] and Professor Ayrton.[3] Kapp proposes that the speeds of rotation shall be assumed to vary inversely as the linear dimensions, so as to put all machines into equal conditions as regards strains from centrifugal force, and that all the similar machines shall be considered as being worked up to the same safe limit of heating. This involves that the work wasted internally in heat shall be proportional to surface or as $1 : n^2$. The resistances, both magnetic and electric, of the field-magnets wiil be proportioned to n^{-1}, and the exciting powers to $n^{\frac{3}{2}}$. The intensities of field will be proportional to $n^{\frac{1}{2}}$, and the electromotive-forces to $n^{\frac{3}{2}}$. The diameters of wires allowed are as n^1 on the magnets and $n^{\frac{3}{2}}$ on the armatures; the resistances of armatures will be proportional to n^{-2}, and the permissible current to n^2. It follows at once that the capacities of the machine (in watts) will vary as $n^{3\frac{1}{2}}$, whilst the work wasted will vary as n^1: hence the economic coefficient will increase with the size of the machine. Kapp gives the cost of machines as proportional to $n^{2\frac{1}{2}}$, whence it follows that the cost of a dynamo per unit of output (say per lamp) varies inversely as its linear dimensions. He gives the following illustrative table:—

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[1] *Centralblatt für Elektrotechnik*, viii. 544, 594, and 743, 1886.

[2] *Proc. Inst. Civil Engineers*, lxxxiii. 36, 1886.

[3] *Ibid.*, p. 116.

Diameter of armature (inches)	10	15
Revolutions per minute	1000	670
Number of glow-lamps	150	620
Weight (in hundredweights)	10	34
Price	100*l.*	276*l.*
Price per lamp	13*s.* 4*d.*	8*s.* 11*d.*
Electrical efficiency (per cent.)	80	89

Professor Ayrton assumes that the speeds of similar machines may be safely put as inversely proportional to the square-roots of the linear dimensions or as to $n^{-\frac{1}{2}}$ instead of n^{-1}, for the number and the strength of the binding wires could easily be increased in the larger machines. In the larger machines the smaller relative space required for clearance makes admissible the increase of the current in proportion to n^2. But this increased current would magnetize the iron more highly in proportion, and the electromotive force would be greater than $n^{\frac{3}{2}}$, probably nearer $n^{1.7}$, bringing up the capacity to be proportional to $n^{3.7}$.

The common opinion of dynamo constructors appears to be that the capacity of dynamos is, for similar machines, a little greater than in proportion to the weight.

Esson[1] has discussed this question from the point of view of multipolar machines, and finds it a matter of appropriate design whether the efficiency increases or decreases when machines are enlarged in size.

[1] *Journal Inst. Electrical Engineers*, xx. 265, 1891.

CHAPTER VI.

MAGNETIC PRINCIPLES; AND THE MAGNETIC PROPERTIES OF IRON.

As all dynamo-electric machines are based on magnetic principles, it is needful that these should be understood fully. Inasmuch as the field-magnets of dynamos are electromagnets, the iron cores of which are excited by electric currents circulating in surrounding coils, it becomes a matter of primary importance to us to know what is the law that governs the electromagnet. If we once know the relation that subsists between the exciting current and the magnetism that is produced by it, we can apply this knowledge to the design of dynamos: for such knowledge will enable us to calculate beforehand the size of field-magnet and the number and gauge of coils that will be required in a dynamo that is to furnish any given amount of electric energy. It will be necessary first to define the terms used; then we shall give some account of the facts and of the properties of iron of different kinds; incidentally there will follow an account of the various algebraic rules that have been suggested to represent approximately the law of the electromagnet. In Chapter VII. follow some all-important considerations respecting the magnetic circuit and its theory; some examples and useful rules will be given, and lastly, the various forms given to field-magnets will be discussed and calculations respecting them will be given.

DEFINITIONS AND GENERAL PROPERTIES.[1]

Unit of Magnetism.—The unit quantity of magnetism (as accepted internationally) at any magnetic pole, is defined as being such that it will repel a similar equal quantity situated at a distance of one centimetre, in air, with a force of 1 *dyne.*

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[1] Any one who is not familiar with the measurement of magnetic quantities ought very carefully to read Appendix A, on Electric and Magnetic

Intensity of Magnetic Field.—We have seen in Chapter III. that every magnet is surrounded by a certain "field," within which magnetic force is observable. We may completely specify the properties of the field at any point by measuring the *strength* and the *direction* of that force—that is, by measuring the "*intensity of the field*" and the direction of the lines of force. *The "intensity of the field" at any point is measured by the force with which it acts on a unit magnetic pole placed at that point.* Hence, *unit intensity of field is that intensity of field which acts on a unit pole with a force of one dyne.* There is therefore a field of unit intensity at a point one centimetre distant from the pole of a magnet of unit strength. Suppose a magnet pole, whose strength is m, placed in a field at a point where the intensity is $\mathbf{H}$, then the force will be m times as great as if the pole were of unit strength, and the amount of the force (in dynes) can be calculated by simply multiplying together the strength of the magnetism of the pole and the intensity of the field; or

$$f = m \times \mathbf{H}$$

Magnetic Lines.—It is possible, in every magnetic field, to draw through any given point, a line in such a direction that it represents the direction of the magnetic force at that point of the field (Fig. 10, p. 24). The iron filing curves formed round magnets show the forms of the otherwise invisible magnetic lines. Even when such lines are not actually drawn, they may be supposed to be drawn; we may even conceive the whole of the space in the magnetic field to be traversed by such lines. Faraday was the first to give a quantitative significa-

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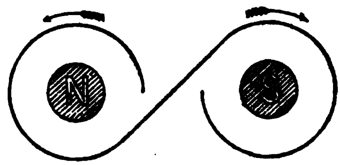
Units. It is also strongly recommended that the reader should make himself familiar with the elementary theory of magnetic phenomena. The Author's 'Elementary Lessons in Electricity and Magnetism,' published by Messrs. Macmillan and Co., will explain the terms and fundamental facts. The Author's recent work on 'The Electromagnet,' published by Messrs. Spon, contains a fuller account of the magnetic properties of iron, and of the design and construction of electromagnets.

tion to the conception of magnetic lines. We may use them to specify not only the *direction* but also the *magnitude* of the magnetic forces by adopting the following convention:—Let there be drawn as many lines per square centimetre as there are dynes (per unit pole) of force at the point in question. The symbol H may then be read to mean *either* the number of dynes on a unit pole or the number of lines per square centimetre.

We take as a measure of the intensity of the field at any point the number of lines of force that pass through a square centimetre of surface placed across the field at that point. *It follows that a unit magnet pole will have 4π lines of force proceeding from it:* for there is unit field at unit distance away, or one line of force per square centimetre; and there are 4π square centimetres of surface on a sphere of unit radius drawn round the pole. A magnet whose pole strength is m, has therefore $4\pi m$ lines of force running through the steel and diverging at its pole.

Polarity.—It is a familiar fact that the polarity of an electromagnet depends upon the sense in which the current is flowing around it. Various rules for remembering the relation of the electric flow and the magnetic force have been given. One of them that is useful is that when one is looking at the north pole of an electromagnet, the current will be flowing around that pole in the sense opposite to that in which the hands of a clock are seen to revolve. This necessitates the connexion of the bobbins of a two-pole electromagnet in such a way that the currents shall circulate as indicated in the manner depicted in Fig. 84. Another useful rule suggested by Maxwell, is illustrated by Fig. 85, namely, that the sense of the circulation of the current (whether right or left-handed), and the positive direction of the resulting magnetic

FIG. 84.



CIRCULATION OF CURRENT AROUND A TWO-POLE ELECTROMAGNET.

force, are related together in the same way as the rotation and the travel of a right-handed screw are associated with forward travel. Right-handed circulation of a current is associated with a magnetic force tending to produce north polarity at the forward end of the core.

FIG. 85.

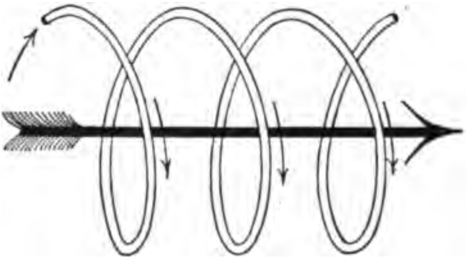


DIAGRAM ILLUSTRATING RELATION OF MAGNETIZING CURRENT AND RESULTING MAGNETIC FORCE.

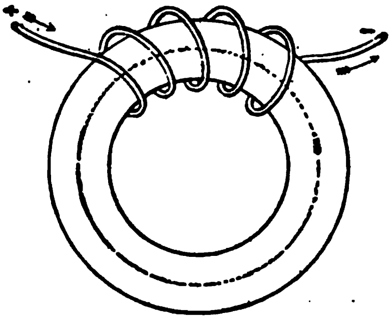
ELECTROMAGNETIC RULES.

Since the field-magnet is in almost all dynamos an electromagnet of iron magnetized by keeping an electric current circulating around it, it will be necessary to lay down a few elementary propositions dealing with the relation between electric currents and magnetic forces.

1. *Magnetomotive Force*, or Total Magnetizing Power of Electric Current circulating in a Coil.—It is found that when a current flows along in a copper wire that is coiled in several turns around a core, and is thus made to circulate around an interior magnetic circuit, the magnetizing power or tendency of this circulation of electricity is proportional both to the strength of the current so circulating and to the number of turns in the coil. If other things are equal, the total magnetizing power depends on nothing else but these two matters; being independent of the size or material of the wire, and of its shape, and is the same whether the spirals are close together or wide apart. If S stands for the number of *spirals* in the coil, and i be the number of *amperes* of current

that are flowing, then S multiplied by i will be the number of *ampere-turns* of circulation of current. It is experimentally proved that twenty amperes circulating around five turns exert precisely the same magnetizing power as one ampere circulating one hundred times, or as one hundred amperes circulating once around the core. In each of these cases the circulation of current is one hundred ampere-turns. To calculate from this the value, in absolute C.G.S. units, of the magnetomotive force, it is requisite to multiply the ampere-turns by $\frac{4}{10}\pi$, or by 1·257. Or, in symbols.

FIG. 86.



MAGNETIZING COIL WOUND AROUND A MAGNETIC CIRCUIT.

$$\text{Magnetomotive force} = 1{\cdot}257 \times S\,i.$$

It is possible to avoid the use of this multiplier by taking the ampere-turns themselves as the magnetomotive force. In that case one applies a coefficient to the calculation of the reluctance of the circuit (see p. 409).

Some writers call the magnetomotive force the "line-integral of the magnetic forces."

2. *Intensity of Magnetic Force at any point in a long Magnetizing Coil.*—The preceding expression for the total magnetizing power of a coil does not give any information about the variation of the magnetic force at different parts. If in Fig. 86 a closed curve be drawn (the dotted curve) passing through all the spirals, and the question be asked, "What is the intensity of the magnetic force at various points

on this curve?" it must be replied that the intensity of the force will vary greatly from point to point, being greatest at the middle of that part of the curve which lies within the spirals. If a uniformly-wound coil were constructed of very great length (say at least one hundred times its own diameter), the intensity of the magnetic force would be very nearly uniformly great all along its axis, until quite close to the ends of the coil, where it rapidly falls off. The expression for the value of **H** at any point along the axis (save near the ends) of such a long coil is found by considering the magnetomotive force as distributed uniformly along its length; or, in symbols, where l stands for the length of the coil, in centimetres.

$$\mathbf{H} = \frac{4\pi}{10}\frac{Si}{l} = 1 \cdot 257 \text{ times the ampere-turns per centimetre of length.}$$

Or, if the length is given in inches:

$$\mathbf{H} = 0{\cdot}495 \text{ times the ampere-turns per inch.}$$

Or, if it is desired to express the intensity of the magnetic force in lines *per square inch* (see p. 142) instead of per square centimetre, we shall have: —

$$\mathbf{H}_{\prime\prime} = 3{\cdot}192 \times \text{the ampere-turns per inch.}$$

In the case where a wire is wound in an annular coil upon an iron ring, so that there are no ends to the coil, **H** is uniform at all points along the closed curve drawn within the coil, and is calculated as above, taking the mean length along the body of the ring as l. It is obvious that when **H** is uniform $\mathbf{H} \times l$ gives the total magnetizing power or magnetomotive force.

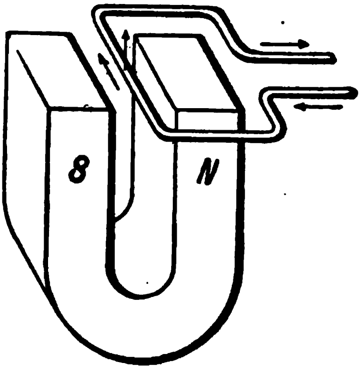
3. *Intensity of Magnetic Force at centre of a single Ring.*— At the centre of a single ring or circular loop of wire carrying current of i amperes, and of radius r centimetres, the intensity of the magnetic force is calculated by the formula

$$\mathbf{H} = \frac{2\pi i}{10\, r} = 0 \cdot 6284 \times \frac{\text{amperes}}{\text{radius}}.$$

This is the case of a tangent galvanometer ring; the number needing to be multiplied by S, if there are S turns in the ring.

4. *Force on Conductor* (carrying current) *in a Magnetic Field.*—Suppose a magnetic field is furnished by a permanent magnet (Fig. 87), and that a conducting wire carrying an electric current is brought into the magnetic field, it is observed to experience a mechanical force in a direction at right angles to its own length, and at right angles to the magnetic lines of the field. In the figure the direction of the flux of magnetic lines is horizontal from right to left between the limbs of the magnet; the direction of the current is horizontal from front to back; and the resulting mechanical force will urge the conductor upward, as shown by the arrow. Reversing the current would, of course, result in a downward force.

Fig. 87.



Action of Magnetic Field on Conductor carrying Current.

The magnitude of this force can be calculated as follows:—Assume the field to be of uniform intensity $\mathbf{H}$, and that the length (centimetres) of conductor lying squarely across the field is l. Then if i is the number of amperes of current, the force (in dynes) will be given by the rule

$$f = \mathbf{H}\, l\, i \div 10 = \mathbf{H}_{{\prime\prime}}\, l''\, i \div 25{\cdot}4\overset{0}{\cancel{8}}$$

or in grains' weight

$$f = \mathbf{H}_{{\prime\prime}}\, l''\, i \div 161.$$

5. *Work done by Conductor* (carrying current) *in moving across Magnetic Field.*—If the conductor moves across a breadth b (centimetres) of the magnetic field, the work done will be expressed (in ergs) as follows:—

$$w = f\, b = b\, \mathbf{H}\, l\, i \div 10.$$

But $b\, l$ is the area of field swept out; and this area multiplied by the number of magnetic lines per square centimetre (**H**) gives the whole number N of magnetic lines cut in the operation; whence

$$w = N\, i \div 10.$$

Proof:—This matter may be independently deduced as follows:—By definition of electric potential, the work done in moving Q units of electricity through difference of potential $V_1 - V_2$ is

$$w = Q\,(V_1 - V_2).$$

But in cutting N lines of magnetic field in a time of t seconds there is generated an electromotive-force $= N \div t$, and this constitutes the difference of electric potential $V_1 - V_2$ and may be substituted for it.

Further, if the current i is expressed in amperes, the quantity Q of electricity expressed in absolute C.G.S. units conveyed through the circuit in t seconds, will be $= i\,t \div 10$.

Substituting the latter value for Q and the former for $V_1 - V_2$, one at once obtains the result:—

$$w = N\, i \div 10, \text{ as before.}$$

Intensity of Magnetization; Magnetic Susceptibility and Magnetic Permeability.—When a piece of magnetic metal is placed in a magnetic field, some of the lines of magnetic force run through it and magnetize it. The intensity of its magnetization will depend upon the intensity of the field into which it is put and upon the metal itself. There are two ways of looking at the matter, each of which has its advantages. We may think of the magnetism of the iron or other metal as something resident on the polar surfaces, and expressed therefore in units of magnetism: this is the old way, adopted at a time when magnetism was regarded as a fluid. Or, we may think about the internal condition of the piece of metal, and about the number of magnetic lines that are running through it and emerging from it into the surrounding space. This is the more modern way.

The fact that soft iron placed in the magnetic field becomes highly magnetic, may then be expressed in the following two ways:—(1) when iron is placed in a magnetic field the magnetic lines gather themselves up and run in greater quantities through the space now occupied by iron, for iron is very *permeable* to the magnetic lines,[1] or is a good conductor of them; (2) iron when placed in the magnetic field develops strong poles on its end surfaces, being highly *susceptible* to the reception of magnetism. Each of these ideas may be rendered exact by the introduction of coefficients of *permeability* and of *susceptibility* respectively.

The *permeability or coefficient of magnetic induction* is based on the notion of the whole mass of iron being permeated by the magnetic lines. The number of magnetic lines that run through unit area of cross-section, at any point is called "the magnetic induction" at that point; it is denoted[2] by the letter **B**. The ratio between the magnetic induction and the magnetizing force **H** producing it is expressed by a numerical coefficient of induction, or *permeability*, μ. We therefore write

$$\mathbf{B} = \mu \mathbf{H}$$

or

$$\mu = \frac{\mathbf{B}}{\mathbf{H}}$$

This coefficient is always positive: for empty space or air it is 1; for magnetic materials it is greater than 1; for diamagnetic materials it is slightly less than 1. The student may think of it in the following way: Suppose a certain magnetizing force to act in a certain direction, there would naturally result from its action induction along a certain number of magnetic lines (or so-called lines of force), and in air the number of lines would numerically represent the magnetizing force. But if the space considered were occupied by iron the same magnetizing force would induce many more lines; iron having a sort of multiplying power, or specific inductive capacity, or conductivity, for the magnetic lines. For example, a certain specimen of iron, when subjected to a magnetic force capable of creating, in air, 50 magnetic lines to the square centimetre, was found to be permeated by no fewer than 16,062 magnetic lines per square centimetre. Dividing the latter figure by the former, gives as the value of the permeability at this stage of the magnetization 321, or the permeability of the iron is 321 times that of air. The permeability of such non-magnetic materials as silk, cotton, and other insulators, also of brass, copper, and all the non-magnetic metals, is taken as 1, being practically the same as that of the air.

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[1] Some authorities make a distinction between magnetic lines of force (those which would exist in air) and magnetic lines of induction, or those which exist in any material over and above the number which would exist in air alone. The distinction is entirely useless, for all magnetic lines have the same properties. I call them all simply "magnetic lines."

[2] The following are the various ways of expressing the three definitions:—

B—The internal magnetization.
The magnetic induction.
The induction.
The intensity of the induction.
The permeation.
The number of lines per square centimetre in the material.

H—The magnetizing force at a point.
The magnetic force at a point.
The intensity of the magnetic force.
The number of lines per square centimetre that there would be in air.

μ—The magnetic permeability.
The permeability.
The specific conductivity for magnetic lines.
The magnetic multiplying power of the material.

The *susceptibility* or *coefficient* of (surface) *magnetization* is now seldom used. Suppose a bar magnet to have m units of magnetism on each pole, and the length between the two poles to be l, the product $m \times l$ is called its *magnetic moment*; and the magnetic moment divided by its volume is called its *intensity* of magnetization; this term being intended, though based on the surface-unit of pole-strength, to convey an idea as to the internal magnetic state. Now, supposing this intensity of magnetization—for which the symbol is $\mathbf{I}$—were due to the iron having been put into a magnetic field of intensity $\mathbf{H}$, the ratio between these two is called the *susceptibility*, and for it the symbol k is used. So we may write

$$\mathbf{I} = k\,\mathbf{H},$$

or

$$k = \frac{\mathbf{I}}{\mathbf{H}}$$

This may be looked upon as saying that for every magnetic line in the magnetizing field there will be k units of magnetism on the end surface of the bar of iron.

These two coefficients are connected in the following way; since each line produces k units of magnetism, and from each unit 4π lines proceed outwards, there will be $4\pi k$ lines added by the iron to each line in the air: or

$$\mu = 1 + 4\pi k$$

and

$$\mathbf{B} = \mathbf{H} + 4\pi\mathbf{I}.$$

This mode of expressing the facts is, however, complicated by the fact of the tendency in all kinds of iron to magnetic saturation. In all kinds of iron the magnetizability of the material becomes diminished as the actual magnetization is pushed further. In other words, when a piece of iron has been magnetized up to a certain degree, it becomes from that degree onward, less permeable to further magnetization, and though actual saturation is never reached, there is a practical limit beyond which the magnetization cannot well be pushed. Joule was one of the first to establish this tendency toward magnetic saturation. Modern researches have shown numerically how the permeability diminishes as the magnetization is pushed to higher stages. The practical limit of the magnetization, **B**, in good wrought iron, is about 20,000 magnetic lines to the square centimetre, or about 125,000 lines to the square inch; and, in cast iron the practical saturation limit is nearly 12,000 lines per square centimetre, or about 70,000 lines per square inch.

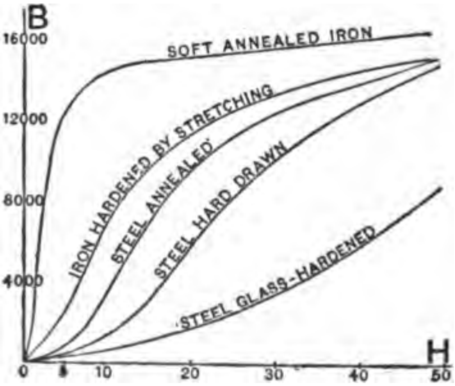
In designing electromagnets, before calculations can be made as to the size of a piece of iron required for the core of a magnet for any particular purpose, it is necessary to know the magnetic properties of that piece of iron; for it is obvious that if the iron be of inferior magnetic permeability, a larger piece of it will be required in order to produce the same magnetic effect as might be produced with a smaller piece of higher permeability. Or again, the piece having inferior permeability will require to have more copper wire wound on it;

for in order to bring up its magnetization to the required point, it must be subjected to higher magnetizing forces than would be necessary if a piece of higher permeability had been selected.

CURVES OF MAGNETIZATION.

A convenient mode of studying the magnetic facts respecting any particular brand of iron is to plot on a diagram the curve of magnetization—*i. e.* the curve in which the values, plotted horizontally, represent the magnetic force, **H**, and the values plotted vertically those that correspond to the respective magnetization, **B**. In Fig. 88, which is modified from the researches of Professor Ewing,[1] are given five curves, relating to soft iron, hardened iron, annealed steel, hard-drawn steel, and glass-hard steel. It will be noticed that all these curves have the same general form. For small values of **H** the values of **B** are small, and as **H** is increased **B** increases also. Further, the curve rises very suddenly, at least with all the softer sorts of iron, and then bends over and becomes nearly horizontal. When the magnetization is in the stage below the bend of the curve, the iron is said to be

FIG. 88.



CURVES OF MAGNETIZATION OF VARIOUS SORTS OF IRON.

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[1] *Phil. Trans.*, 1885.

far from the state of saturation. But when the magnetization has been pushed beyond the bend of the curve the iron is said to be in the stage approaching saturation; because at this stage of magnetization it requires a large increase in the magnetizing force to produce even a very small increase in the magnetization. It will be noted that for soft wrought iron the stage of approaching saturation sets in when **B** has attained the value of about 16,000 lines per square centimetre; or when **H** has been raised to the value of about 50. As we shall see, it is not economical to push **B** beyond this limit; or in other words it does not pay to use stronger magnetic forces than those of about **H** = 50.

METHODS OF MEASURING PERMEABILITY.

There are four sorts of experimental methods of measuring permeability:—

I. Magnetometric methods.
II. Balance methods.
III. Inductive methods.
IV. Traction methods.

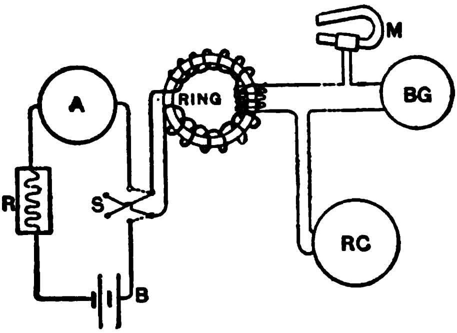
I. *Magnetometric Methods.*—These consist in surrounding a bar of the iron in question by a magnetizing coil, and observing the deflection its magnetization produces in a magnetometer.

II. *Balance Methods.*—These methods are a variety of the preceding; a compensating magnet being employed to balance the effect produced by the magnetized iron on the magnetometer needle. The method has received a more definite application in the magnetic balance of Professor Hughes. Neither of these methods are, however, to be compared with those that follow.

III. *Inductive Methods.*—There are several varieties of these, but all depend on the generation of a transient induction current in an exploring coil which surrounds the specimen of iron; the integral current being proportional to the number of magnetic lines introduced into, or withdrawn from the circuit of the exploring coil. Three varieties may be mentioned.

(*A.*) *Ring Method.*—In this method, due to Kirchhoff, the iron under examination is made up into a ring, which is wound with a primary, or exciting coil, and with a secondary, or exploring coil. Determinations on this plan have been made by Stoletow, Rowland, Bosanquet, and Ewing; also by Hopkinson. Rowland's arrangement of the experiment is shown in Fig. 89, in which B is the exciting battery; S the switch for turning on or reversing the current in the exciting coil wound on the iron ring; R a variable resistance; A an amperemeter; and B G the ballistic galvanometer, the first swing of which measures the integral induced current. R C is an earth-inductor or reversing coil wherewith to calibrate the readings of the galvanometer; and above is an arrangement of a coil and a magnet to assist in bringing the swinging needle to rest between the observations. The exciting coil and the exploring coil are both wound upon the ring; the former is distinguished by being drawn with a thicker line. The usual mode of procedure is to begin with a feeble exciting current, which is suddenly reversed, and then reversed back. The current is then increased, reversed, and re-reversed; and so on, until the strongest available points are reached. The values of the magnetizing force H are calculated from the observed value of the current by the

FIG. 89.



RING METHOD OF MEASURING PERMEABILITY (Rowland's arrangement).

following rule:—If the strength of the current, as measured by the amperemeter, be i, the number of spires of the exciting coil S, and the length in centimetres of the coil (*i. e.* the mean circumference of the ring) be l, then **H** is given (see p. 126) by the formula—

$$\mathbf{H} = \frac{4\pi}{10} \times \frac{S\,i}{l} = 1{\cdot}257 \times \frac{S\,i}{l}.$$

Bosanquet, applying this method to a number of iron rings, obtained some important results, and settled the debated question whether the outer layers of an iron core shield the inner layers from the influence of magnetizing forces. Were this the case, thin rings should show higher values of **B** than do the thicker rings; but Bosanquet found nothing of the kind.

(*B.*) *Bar Method.*—This method consists in employing a long bar of iron instead of a ring. It is covered from end to end with the exciting coil, but the exploring coil consists of but a few turns of wire situated just over the middle part of the bar. Rowland, Bosanquet, and Ewing have all employed this variety of method; and Ewing specially used bars, the length of which was more than a hundred times their diameter, in order to get rid of errors arising from end-effects.

(*C.*) *Divided Bar Method.*—This method, due to Dr. Hopkinson,[1] illustrated by Fig. 90, employs a block of annealed wrought iron about 18 inches long, 6½ inches wide, 2 inches deep, out of the middle of which is cut a rectangular space to receive the magnetizing coils. The test samples of iron consist of two rods, each 12·65 mm. in diameter, turned carefully true, and slide in through holes bored in the ends of the iron block. These two rods meet in the middle, their ends being faced true so as to make a good contact. One of them is secured firmly, and the other has a handle fixed to it, by means of which it can be withdrawn. The two large magnetizing coils do not meet, a space being left between them. Into this space is introduced the little exploring coil, wound upon an ivory bobbin, through the eye of which passes the end of the movable rod. The exploring coil is connected to the ballistic galvanometer, B G, and is attached to an india-rubber spring (not shown in the figure), which, when the rod is suddenly pulled back, causes it to leap entirely out of the magnetic field. The exploring coil had 350 turns of fine wire; the two magnetizing coils had 2008 effective turns. The magnetizing current, generated by a battery, B, of eight Grove cells, was regulated by a variable liquid resistance, R, and by a shunt resistance. A reversing switch and an amperemeter, A, were included in the magnetizing circuit. By means of this apparatus the sample rods to be experimented upon could be submitted to any magnetizing forces, small or large, and the actual magnetic condition could be examined at any time by breaking the circuit and simultaneously withdrawing the movable rod. This apparatus, therefore, permitted the observation separately of a series of increasing (or decreasing) magnetizations without any intermediate reversals of the entire current.

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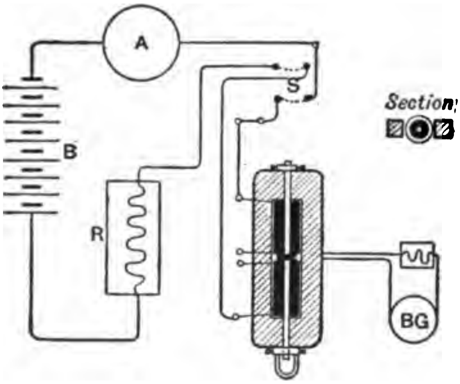
[1] *Phil. Trans.*, p. 456, 1885.

FIG. 90.



HOPKINSON'S DIVIDED BAR METHOD OF MEASURING MAGNETIC PERMEABILITY.

The results obtained by Hopkinson are described on pp. 139 to 145.

To facilitate the operation of making observations on new brands of iron, Mr. J. Swinburne has recently[1] devised a method of experimenting which obviates the use of a ballistic galvanometer. The reader is referred to the original paper for further details.

TRACTION METHODS.

Another group of methods of measuring permeability is based upon the law of magnetic traction. Of these there are several varieties.

(*D.*) *Divided Ring Method.*—Mr. Shelford Bidwell has kindly lent me the apparatus with which he carried out this method. It consists of a ring of very soft charcoal iron rod 6·4 mm. in thickness, the external diameter being 8 cm., sawn into two half rings, and then each half carefully wound over with an exciting coil of insulated copper wire of 1929 convolutions in total. The two halves fit neatly together; and in this position it constitutes practically a continuous ring. When an exciting current is passed round the coils, both halves become magnetized and attract one another; the force required to pull them asunder is then measured. According to the law of traction, which will occupy us in the second lecture, the tractive force (over a given area of contact) is proportional to the square of the number of magnetic lines that pass from one surface to the other through the contact joint. Hence the force of traction may be used to determine **B**; and on calculating **H** as before, we can determine the permeability. The Table IV., on p. 147, gives a summary of Mr. Bidwell's results.

(*E.*) *Divided Rod Method.*—In this method, also used by Mr. Bidwell, an iron rod hooked at both ends was divided across the middle, and placed within a vertical surrounding magnetizing coil. One hook was hung up to an overhead support: to the lower hook was hung a scale-pan. Currents of gradually increasing strength were sent around the magnetizing coil from a battery of cells, and note was taken of the greatest weight which could in each case be placed in the scale-pan without tearing asunder the ends of the rods.

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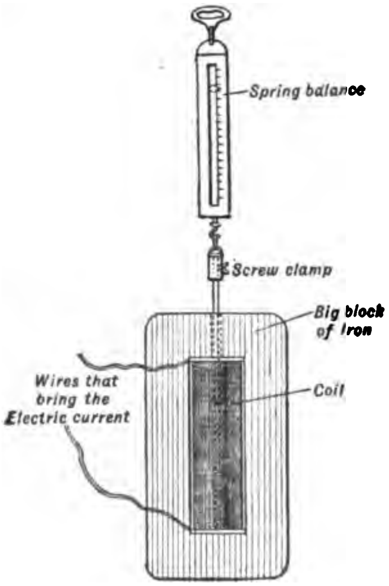
[1] See *The Electrician,* xxv. 648, October 10, 1890.

Fig. 91.



The Permeameter.

(*F.*) *Permeameter Method.*—This is a method devised for the purpose of testing specimens of iron. It is essentially a workshop method as distinguished from a laboratory method. It requires no ballistic galvanometer; and the iron does not need to be forged into a ring or wound with a coil. For carrying it out a simple instrument is needed, which the author denominates as a *permeameter.* Outwardly it has a general resemblance to Dr. Hopkinson's apparatus, and consists simply (Fig. 91) of a rectangular piece of soft wrought iron slotted out to receive a magnetizing coil, down the axis of which passes a brass tube. The block is 12 inches long, 6½ inches wide, and 3 inches in thickness. At one end the block is bored to receive the sample of iron that is to be tested. This consists simply of a thin rod about a foot long, one end of which must be carefully surfaced up. When it is placed inside the magnetizing coil, and the exciting current is turned on, the rod sticks tightly at its lower end to the surface of the iron block; and the force required to detach it (or rather the square root of that force) is a measure of the permeation of the magnetic lines through its end face. In the first permeameter which was constructed, the magnetizing coil is 13·64 cm. in length, and has 371 turns of wire. One ampere of exciting current consequently produces a magnetizing force of $\mathbf{H} = 34$. The wire is thick enough to carry

80 amperes, so that it is easy to reach a magnetizing force of 1000. In a simple experiment the current used was 25 amperes. Two rods were taken of "charcoal iron" and "best iron" respectively, both of quarter-inch square stuff. A spring balance was used, graduated carefully and provided with an automatic catch, so that its index stops at the highest reading. The tractive force of the "charcoal" iron was about 12½ lb., while that of the "best" iron was only 7½ lb., so that **B** was about 19,000 in the charcoal iron, and **H** being 850, μ was about 22·3.

The formula for calculating **B** when the core is thus detached by a pull of P pounds, the area of contact being A square inches, is as follows:—

$$\mathbf{B} = 1317 \times \sqrt{P \div A} + \mathbf{H}.$$

The reason for adding **H** in the formula is that in this instrument the coil remains fixed, the core only being moved. Hence the pull is that due to **B** − **H** lines.

(*G.*) *Traction Balance Method.*—Dr. H. G. Du Bois has recently described[1] a method in which the specimen of iron is placed within a coil between two cheeks of iron, thus constituting part of a magnetic circuit, of which another part is constituted by an iron beam, the attraction of which is measured, and thus the flux calculated.

RESULTS OF EXPERIMENTS ON DIFFERENT BRANDS OF IRON.

Thirty-five samples of various irons of known chemical composition were examined by Hopkinson, the two most important for present purposes being an annealed wrought iron and a grey cast iron, such as are used by Messrs. Mather and Platt in the construction of dynamo machines. Hopkinson embodied his results in curves, from which it is possible to construct, for purposes of reference, numerical tables of sufficient accuracy to serve for future calculations.

In Fig. 92 are given curves of magnetization for *annealed*

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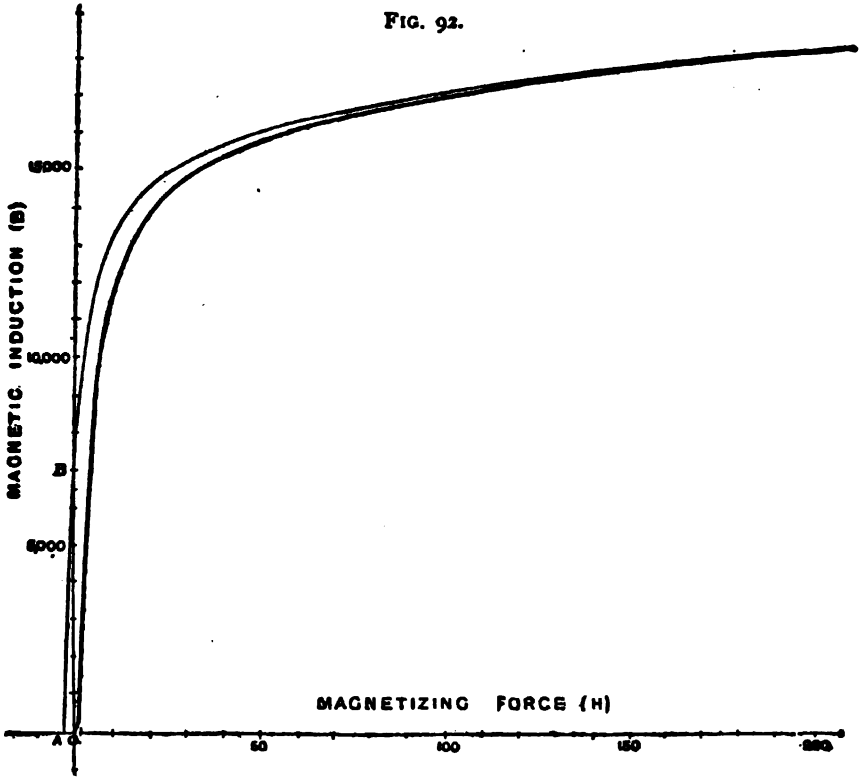
[1] *The Electrician*, xxvii. 635, Oct. 9, 1891.

wrought iron, obtained by the second method of experimenting by Dr. J. Hopkinson.[1] The black line shows the relation between the intensity of the magnetizing force **H** and the induction **B** during the process of increasing the magnetizing force from zero to about 220; and the light line shows the same relation during the process of decreasing the magnetizing force to zero, and then reversing it so as to remove the residual magnetic induction. Fig. 93 gives similar curves for a sample of *grey cast iron* such as is used by Messrs. Mather and Platt in building parts of dynamo machines.

FIG. 92.



Every sample of iron will show, on being tested, a similar set of facts which can be plotted down as a curve that is chaacteristic of the relation in question; but the curves for cast iron and steel always lie lower than those for wrought iron.

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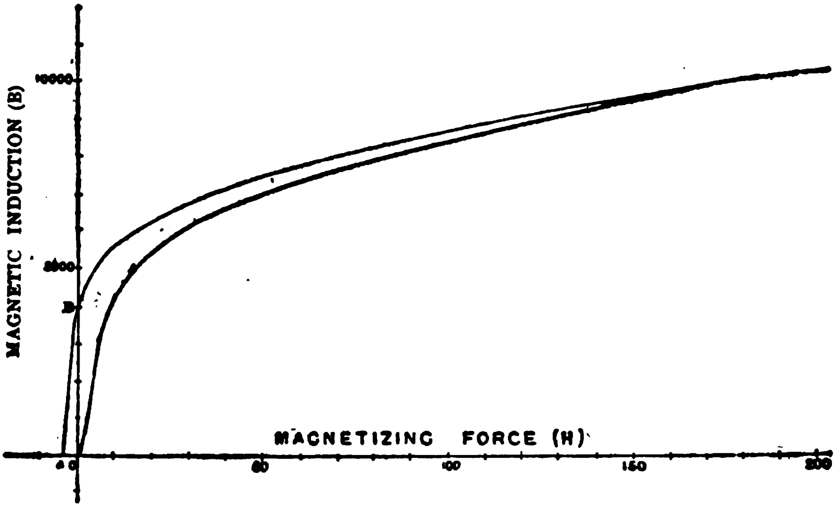
[1] Hopkinson, in *Phil. Trans.*, pt. ii. p. 455, 1885.

Moreover, it will usually be noticed that when a fresh piece of iron or steel is subjected to a gradually increasing magnetizing force, the lowest part of the curve presents near its origin a

FIG. 93.

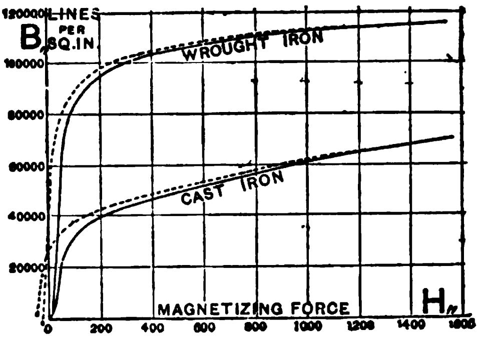


small concavity (see Fig. 93) showing that there is a certain stage where under small magnetizing forces the permeability is greater than at the initial stage. This concavity is more pronounced in the case of hard iron and of steel than in the case of soft iron. But the curves differ in detail even in different specimens of the same sort of iron. In designing dynamos it is convenient to keep for reference a series of curves such as Figs. 92 and 93, made by careful observation on samples of the same iron as it is intended to use in construction.

As we shall require to refer again to these curves when dealing with calculations of the magnetic circuit, it will be well to make the data as complete as possible. Many British engineers are, unfortunately, not familiar with the international metric system, and prefer to have the magnetic facts also stated in terms of square inch units instead of square cm. units. This change has been made in Fig. 94, and the symbols $\mathrm{B}_{\prime\prime}$ and $\mathrm{H}_{\prime\prime}$ are chosen to indicate the numbers of magnetic lines to the square inch in iron and in air respectively. The permeability, or multiplying power of the iron is the same, of course, in either measure. In Table III. are given the corresponding data in square inch measure; and in Table IV. the data in square centimetre measure for the same specimens of iron.

It will be noted that Hopkinson's curves are double, there being one curve for the ascending magnetizations, and a separate one, a little above the former, for descending magnetizations. This is a point of a little importance in designing electromagnets. Iron, and particularly hard sorts of iron, and steel, after having been subjected to a high degree of magnetizing force, and subsequently to a lesser magnetizing force, are found to retain a higher degree of magnetization than if the lower magnetizing force had been simply applied. For example, reference to Fig. 94 shows that the wrought iron, where subjected to a magnetizing force gradually rising from zero to $\mathrm{H}_{\prime\prime} = 200$, exhibits a magnetization of $\mathrm{B}_{\prime\prime} = 95{,}000$; but after $\mathrm{H}_{\prime\prime}$ has been carried up to over 1000, and then reduced again to 200, $\mathrm{B}_{\prime\prime}$ does not come down again to 95,000, but only to 98,000. Any sample of iron which

FIG. 94.



CURVES OF MAGNETIZATION OF IRON. (LINES PER SQ. IN.)

showed great retentive qualities, or in which the descending curve differs widely from the ascending curve, would be liable, if used in constructing a dynamo, to cause the dynamo, after having been highly magnetized, to work at a higher voltage than before. Cast iron shows more of this effect than wrought iron, and hard steel much more than either. For dynamo armatures only the softest iron must be used. For field-magnets most makers prefer wrought iron, but some use well-annealed cast iron. In very few cases is it worth while to make separate calculations for the ascending and descending curves of magnetization, since the magnetization is continually varying up and down. Accordingly, for the numerical data to be employed in calculations we shall employ the mean between the ascending and descending curves. These mean values are given in Tables I. and II.

TABLE I. (SQUARE CENTIMETRE UNITS.)

Annealed Wrought Iron.			Grey Cast Iron.		
B	μ	H	B	μ	H
5000	3000	1·66	4000	800	5
9000	2250	4	5000	500	10
10,000	2000	5	6000	279	21·5
11,000	1692	6·5	7000	133	42
12,000	1412	8·5	8000	100	80
13,000	1083	12	9000	71	127
14,000	823	17	10,000	53	188
15,000	526	28·5	11,000	37	292
16,000	320	50			
17,000	161	105			
18,000	90	200			
19,000	54	350			
20,000	30	666			

The mean values are plotted out from Tables I. and II. on a somewhat larger scale in Figs. 95 and 96, wherein the values of **B** are the abscissæ, and those of **H** are plotted vertically, the scale being on the right-hand side. On the same Figures are given also the plotting of the curves for **B** and μ, which are convenient for the purpose of calculation.

FIG. 95.

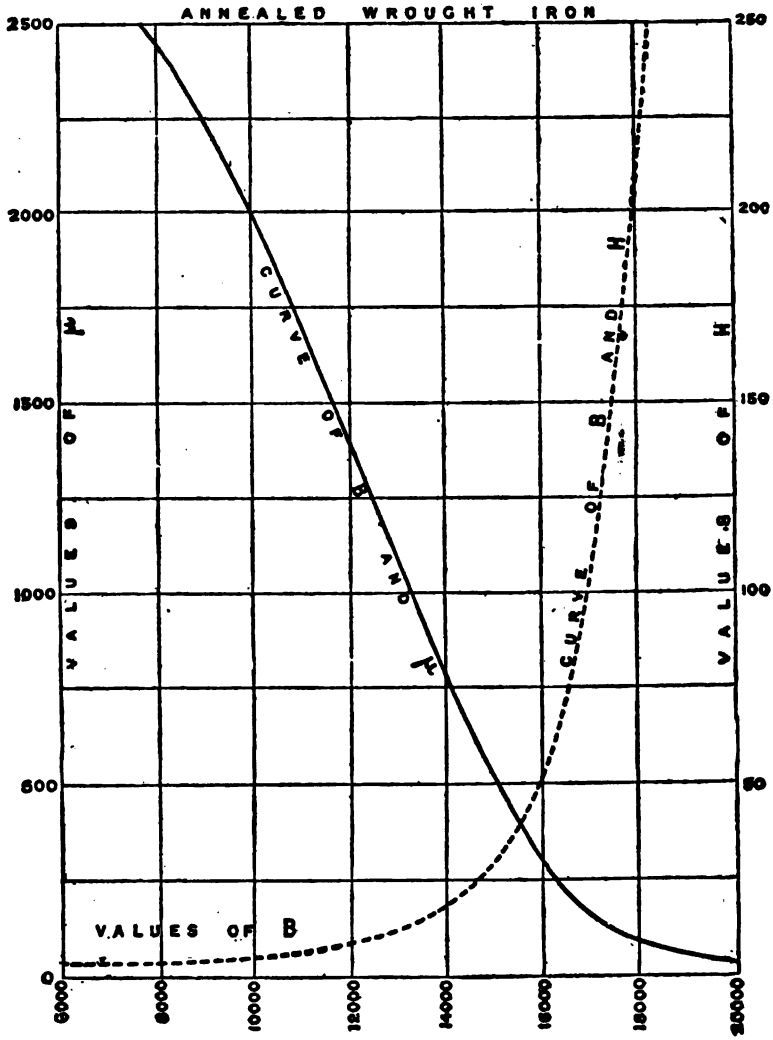


FIG. 96.

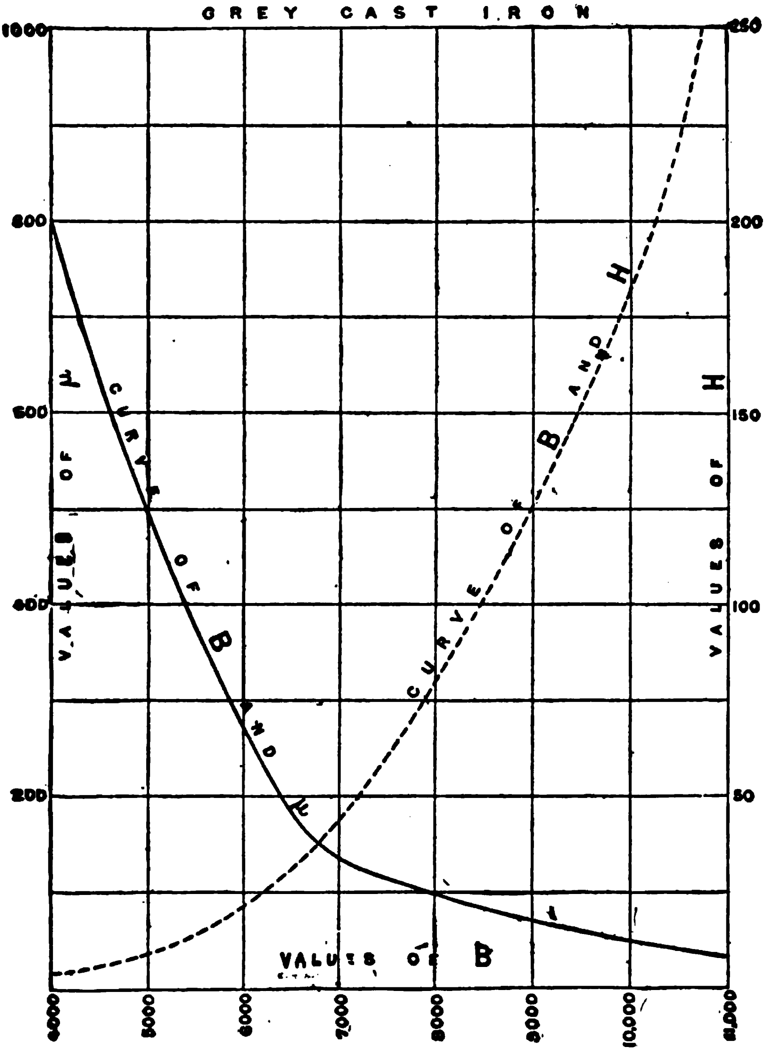

GREY CAST IRON
1000
800
600
400
200
250
200
150
100
50
VALUES OF μ
CURVE OF B AND μ
CURVE OF B AND H
VALUES OF H
VALUES OF B
4000
5000
6000
7000
8000
9000
10,000
11,000

TABLE II. (SQUARE INCH UNITS.)

Annealed Wrought Iron.			Grey Cast Iron.		
$B_{//}$	μ	$H_{//}$	$B_{//}$	μ	$H_{//}$
30,000	2926	10·2	25,000	833	30
40,000	2857	14	30,000	445	53·5
50,000	2392	20·9	40,000	245	163
60,000	2166	27·7	50,000	112	447
70,000	1750	40	60,000	64	940
80,000	1368	63	70,000	40	1750
90,000	856	105			
100,000	407	245			
110,000	161	686			
120,000	64	1850			
130,000	28	4500			
140,000	18	7630			

Bosanquet's data for five specimens of "Crown iron" are as follows:—

TABLE III.—VALUES OF B IN FIVE CROWN IRON RINGS.

Name.	G.	E.	F.	H.	K.
Mean Diam. Bar thickness.	21·5 cm. 2·535.	10·035 cm. 1·298	22·1 cm. 1·292.	10·735 cm. 0·7137	22·725 cm. 0·7544.
H Magnetizing Force.					
0·2	126	73	62	82	85
0·5	377	270	224	208	214
1	1,449	1,293	840	675	885
2	4,564	3,952	3,533	2,777	2,417
5	9,900	9,147	8,293	8,479	8,884
10	13,023	13,357	12,540	11,376	11,388
20	14,911	14,653	14,710	14,066	13,273
50	16,217	15,704	16,062	15,174	13,890
100	17,148	16,677	17,900	16,134	14,837

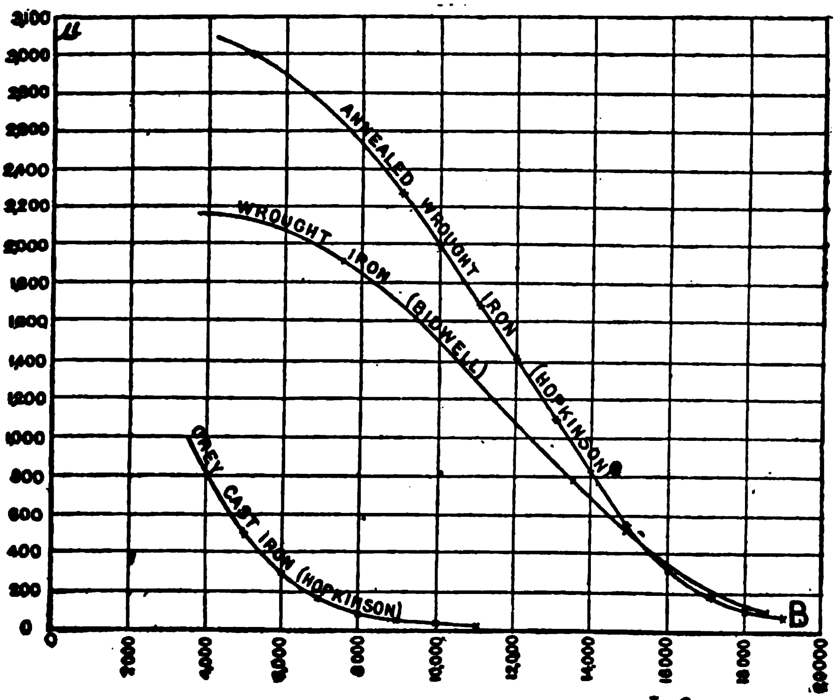
Bosanquet found a ring of Lowmoor iron to surpass all the samples of Crown iron, at **H** = 50 he found **B** over 17,000; and at **H** =100, **B** = 18,300.

Bidwell, who pushed the magnetization further, using the traction method found the following results :—

TABLE IV.—SQUARE CENTIMETRE MEASURE.

Soft Charcoal Iron.		
B	μ	H
7,390	1899·1	3·9
11,550	1121·4	10·3
15,460	386·4	40
17,330	150·7	115
18,470	88·8	208
19,330	45·3	427
19,820	33·9	585

FIG. 97.



A very useful alternative mode of studying the results obtained by experiment is to construct curves, such as those of Fig. 97, in which the values of the permeability are plotted out vertically in correspondence with the values of **B** plotted horizontally, as in Figs. 95 and 96. It will be noticed that in the case of Hopkinson's specimen of annealed wrought iron between the points where $\mathbf{B} = 7000$ and $\mathbf{B} = 16{,}000$, the mean values of μ lie almost on a straight line, and might be approximately calculated from the equation

$$\mu = (17{,}000 - \mathbf{B}) \div 3 \cdot 5.$$

LIMITS OF MAGNETIZATION AND PERMEABILITY.

In reviewing the results obtained, it will be noted that the curves of magnetization all possess the same general features, all tending toward a practical maximum, which, however, is different for different materials. Joule expressed the opinion that *no force of current could give an attraction equal to* 200 *lb. per square inch*, the greatest he actually attained being only 175 lb. per square inch. Rowland was of opinion that the limit was about 177 lb. per square inch for an ordinary good quality of iron, even with infinitely great exciting power. This would correspond roughly to a limiting value of **B** of about 17,500 lines to the sq. cm. This value has, however, been often surpassed. Bidwell obtained 19,820, or possibly a trifle more, as in Bidwell's calculation the value of **H** has been needlessly discounted. Hopkinson gives 18,250 for wrought iron, and 19,840 for mild Whitworth steel. Kapp gives 16,740 for wrought iron, 20,460 for charcoal iron in sheet, and 23,250 for charcoal iron in wire. Bosanquet found the highest value in the middle bit of a long bar to run up in one specimen to 21,428, in another to 29,388, in a third to 27,688. Ewing, working with extraordinary magnetic power by the "isthmus" method,[1] forced up the value of **B** in Lowmoor iron to 31,560 (when μ came down to 3), and subsequently to 45,350. This last figure corresponds to a traction exceeding 1000 lb. to the square inch.

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[1] See *Electrician*, xxv. 307, 1890.

In the following table are given some of Ewing's figures relating to the magnetization of Swedish iron in very strong magnetic fields:—

TABLE V. (Square Centimetre Measure).—SWEDISH IRON.

H	B	μ
1,490	22,650	15·20
3,600	24,650	6·85
6,070	27,130	4·47
8,600	30,270	3·52
18,310	38,960	2·13
19,450	40,820	2·10
19,880	41,140	2·07

Cast iron falls far below these figures. Hopkinson, using a magnetizing force of 240, found the values of **B** to be 10,783 in grey cast iron, 12,408 in malleable cast iron, and 10,546 in mottled cast iron. Ewing, with a magnetizing force nearly fifty times as great, forced up the value of **B** in cast iron to 31,760. Mitis metal, which is a sort of cast wrought iron, being a wrought iron rendered fluid by addition of a small percentage of aluminium, is, as I have found, more magnetizable than cast iron, and not far inferior to wrought iron. It should form an excellent material for the cores of electromagnets.

It was at one time supposed that the values of **B** would show a limiting value at about 20,000, for example, in wrought iron. Ewing's figures obtained with enormous magnetizing forces, show that this is not so ; but on the other hand, they show that **B** — **H** does tend to a limit. In other words, that part of **B** which is directly due to the presence of the iron, does tend to a true saturation limit. This maximum appears to be about 21,360 in wrought iron, and 15,580 in cast iron.

For further magnetic data the reader is referred to the writings of Hopkinson, Bosanquet, and Ewing, particularly to Ewing's chapters on Magnetism in *The Electrician* of 1890–91. A digest of the researches of these authorities is to be found in the author's treatise on "The Electromagnet."

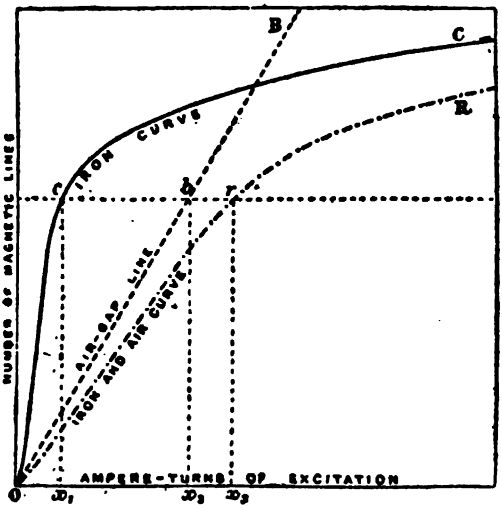
EFFECTS OF AIR-GAP IN MAGNETIC CIRCUIT.

All the preceding results refer exclusively to that which goes on in iron itself, the curves of magnetization referring to the magnetic materials only. They tell us (in terms of **H**) the magnetic force required to drive **B** lines of magnetization through a single cubic cm. of the material. If we are to deal with an actual piece of iron that is more than 1 sq. cm. in cross-section, and more than 1 cm. in length, all that is necessary to represent the facts (so long as we are dealing with magnetization that is entirely internal to the iron) is to change the scale of the curves. For example, suppose we are dealing with an iron ring made of a piece of square bar annealed wrought iron (of the same brand as Hopkinson used), the size of the iron being 2 cm. in the side, and its (mean) length 80 cm.; we shall now have to plot out (instead of **B** and **H**) **N**, the whole flux of magnetic lines within the section of the iron, and **H** l, the line-integral of the magnetizing force around the length of the iron circuit.

Taking the curve of **B** and **H** in Fig. 95, the scales will then have to be changed as follows:—Since the area is 4 sq. cm., **N** at any stage of the magnetization will be equal to four times **B** at that stage. Hence the point on the horizontal scale called **B** = 16,000, will now have to be called **N** = 64,000. And since l, the length of the bar, is 80 cm., the same point that now stands for **H** = 50 on the vertical scale (on the right side), which is the corresponding value of the magnetic force, will have to be called **H** l = 4000. With these changes of scales the curve will then serve to represent the magnetic behaviour of the whole ring; it will tell us how much integral magnetizing force we must exert (by means of a current in a coil) in order to drive up **N**, the total flux of magnetic lines, to any desired amount. If we know **H** l, it is easy to calculate the requisite ampere-turns, because (as shown on p. 125) the ampere-turns multiplied by 1·257 are equal to the line-integral of the magnetizing force.

But if there is an air-gap in the magnetic circuit, or if there is a gap filled with any non-magnetic material, seeing that all these things possess a permeability that is equal to that of air (*i. e.* = 1), it is evident that to force the same number of magnetic lines across a layer of such inferior permeability will necessitate an increase in the amount of magnetizing power that must be applied.

FIG. 98.



CURVE OF MAGNETIZATION OF MAGNETIC CIRCUIT WITH AIR-GAP.

This is made plainer by reference to Fig. 98, in which the curve O *c* C represents the relation between the number of magnetic lines in an iron bar and the number of ampere-turns of excitation ($H\ l \div 1{\cdot}257$) needed to force these magnetic lines through the iron. For example, to reach the height *c*, the excitation has to be of the value represented by the length $O\,x_1$. On the same diagram the line O *b* B represents the relation between the flux of magnetic lines across the air-gap and the ampere-turns required to force these lines across. If the gap were 1 sq. cm. in section, and 1 cm. long, 0·795 ampere-turns of current would produce field $\mathrm{H} = \mathrm{B} = 1$. In this case the gap is supposed to be of larger area and shorter than 1 cm., the line sloping up at such a slope that the length $\mathrm{O}\,x_2$ represents the ampere-turns requisite to bring up the magnetic flux to b, which is at the same height on the scale as a. It is then easy to put the two things together, for the total amount of excitation required to force these magnetic lines through air and iron will (neglecting leakage) be the sum of the separate amounts. The point x_3 is chosen so that $\mathrm{O}\,x_3$ is equal to the sum of $\mathrm{O}\,x_1$, and $\mathrm{O}\,x_2$, or that the distance of point r from the vertical axis is equal to the sum of the respective distances of c and b. If the same thing is done for a large number of corresponding points, the resultant curve $\mathrm{O}\,r\,\mathrm{R}$ may be constructed from the two separate curves. It will be seen then that, in general, the presence of a gap in the magnetic circuit has the effect of causing the magnetic curve to rake over, *the initial slope being determined by the air-gap.*

The student should compare some interesting experiments made in Paris by M. Leduc,[1] who, however; falls into an error respecting tubular cores.

EFFECT OF JOINTS.

Being now in a position to calculate the additional magnetizing power required for forcing magnetic lines across an air-gap, we are prepared to discuss a matter that has been so far neglected, namely, the effect on the reluctance of the magnetic circuit of joints in the iron. Horse-shoe electromagnets are not always made of one piece of iron bent round. They are often made of two straight cores shouldered and screwed, or riveted into a yoke.

It is a matter purely for experiment to determine how far a transverse plane of section across the iron obstructs the flow of magnetic lines. Armatures, when in contact with the cores, are never in perfect contact, otherwise they would cohere without the application of any magnetizing force; they are only in imperfect contact, and the joint offers a considerable magnetic reluctance. This matter has been examined by Professor J. J. Thomson and Mr. Newall, in the Cambridge Philosophical Society's *Proceedings*, in 1887; and recently more fully by Professor Ewing, whose researches are published in the *Philosophical Magazine* for September, 1888: Ewing not only tried the effect of cutting and of facing up with true plane surfaces, but used different magnetizing forces, and also applied various external pressures to the joint. For our present purpose we need not enter into the questions of external pressures, but will summarize in Table VI. the results which Ewing found when his bar of wrought iron was cut across by section planes, first into two pieces, then into four, then into eight. The apparent permeability of the bar was reduced at every cut.

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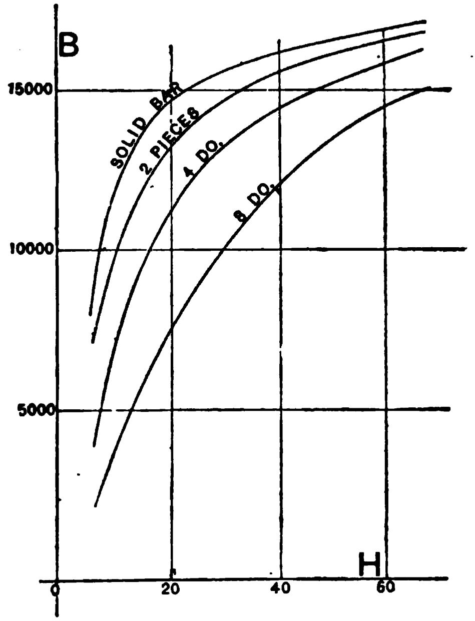
[1] *La Lumière Electrique*, xxviii. 520, 1888.

TABLE VI.—EFFECTS OF JOINTS IN WROUGHT-IRON BAR (not compressed).

H	**B**				Mean thickness of equivalent air-space for one cut.		Thickness of iron of equivalent reluctance per cut.	
	Solid.	Cut in two.	In four.	In eight.	Centimetres.	Inches.	Centimetres.	Inches.
7·5	8,500	6,900	4,809	2,600	0·0036	0·0014	4	1·57
15	13,400	11,550	8,900	5,550	0·0030	0·0012	2·53	1
30	15,350	14,550	12,940	9,800	0·0020	0·0008	1·10	0·433
50	16,400	15,950	15,000	13,300	0·0013	0·0005	0·43	0·169
70	17,100	16,840	16,120	15,200	0·0009	0·0004	0·22	0·087

Suppose we are working with the magnetization of our iron pushed to about 16,000 lines to the sq. cm. (*i e.* about 150 lb. per square inch) traction, requiring a magnetizing force of about **H** = 50; then, referring to Table VI., we see that each joint across the iron offers as much reluctance as would an air-gap 0·0005 of an inch in thickness, or adds as much reluctance as if an additional layer of iron about $\frac{1}{6}$th of an inch thick had been added. With small magnetizing forces the effect of having a cut across the iron with a good surface on it is about the same as though you had introduced a layer of air $\frac{1}{600}$th of an inch thick, or as though you had added to the iron circuit about 1 inch of extra length. With large magnetizing forces, however, this disappears, probably because of the attraction of the two surfaces across that cut. The stress in the magnetic circuit, with high magnetic forces running up to 15,000 or 20,000 lines to the sq. cm., will of itself put on a pressure of 130 to 230 lb. to the square inch,

Fig. 99.



Ewing's Curves for Effect of Joints.

and so these resistances are considerably reduced; they come down in fact to about $\frac{1}{20}$th of their initial value. When Ewing especially applied compressing forces, which were as large as 3200 lb. to the sq. in., which would of themselves ordinarily, in a continuous piece of iron, have diminished the magnetizability, he found the diminution of the magnetizability of iron itself was nearly compensated for by the better conduction of the cut surface. The old surface, cut and compressed in that way, closes up as it were magnetically—does not act like a cut at all; but at the same time you lose just as much as you gain, because the iron itself becomes less magnetizable.

The above results of Ewing's are further represented by the curves of magnetization drawn in Fig. 99. When the faces of a cut were carefully surfaced up to true planes, the disadvantageous effect of the cut was reduced considerably, and under the application of a heavy external pressure almost vanished.

The influence of compression was notable. When a compression of 3210 lb. per sq. in. (= 226 kilogrammes per sq. cm.) was applied to the iron bar, the joint showed, under magnetic forces, a reluctance which decreased as the magnetic force was increased. The following table gives the values of **H** and of **B** in the solid bar, and the bar after being cut, together with the mean thickness of the equivalent air-space.

TABLE VII.—EFFECT OF COMPRESSION ON JOINTS.

H	**B** } under compression of 3210 lb. per sq. inch.		Thickness of mean equivalent air-space. (Millimetres.)
	Solid bar.	Bar cut in eight.	
7·5	7,500	3,600	0·020
10	10,000	4,900	0·019
20	13,900	8,300	0·018
30	15,200	10,700	0·017
50	16,500	13,750	0·011
70	17,200	15,700	0·007

When various loads were tried, the effect of increasing the load, in a weak magnetic field, was practically to close up well-faced joints, as the following table shows.

TABLE VIII.—EFFECT OF VARIOUS LOADS ON JOINTS.

Load, kilos per sq. centimetre.	B (when H = 5).		Thickness of equivalent air-space. (Millimetres.)
	Before cutting.	After cutting and facing.	
0	5,600	4,700	0·022
56·5	5,400	4,670	0·020
131	4,700	4,200	0·017
169·5	4,050	3,800	0·010
226	3,650	3,650	0

EFFECTS OF STRESS.

A piece of iron when placed under stress is somewhat changed in its magnetic properties. If a longitudinal pull is applied to iron whilst it is being magnetized, it is found at first to increase its permeability, whilst a longitudinal push, tending to compress it, decreases its permeability. This is very well shown by the figures given in the second column of the last table, wherein it appears that a compression of 226 kilos. per sq. cm., or nearly $1\frac{1}{2}$ ton per sq. in., brought down the value of B in a wrought-iron bar from 5600 to 3650; or diminished the permeability from 1120 to 730. Stress also impairs the softness of iron. A piece of annealed iron wire hardened by previous stretching, behaves more like a piece of steel, as may be seen by reference to Ewing's curves, Fig. 88, p. 132. Twisting stresses also affect the magnetic quality. The reader should consult Ewing's papers on magnetism.

Another important matter is that all such actions as hammering, rolling, twisting, and the like, impair the magnetic quality of annealed soft iron. Pieces of annealed wrought iron which have never been touched by a tool, provided they do not constitute actually closed magnetic circuits, show hardly any trace of residual magnetization, even after the application of magnetic forces. But the touch of the file will at once spoil it. The continual hammering of the armature of an electro-magnet against the poles may in time produce a similar hardening effect.

EFFECTS OF VIBRATION.

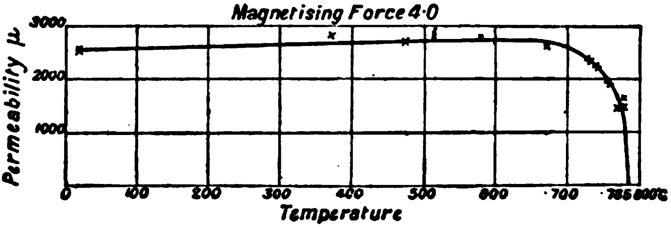
The effects of vibration on magnetism are to diminish all residual actions, and to cause the specimen more rapidly to assume the mean state corresponding to the magnetic force present. If a specimen of soft iron is examined while under rapid vibration, it is found that in it there is scarcely any difference between the ascending and descending curves of magnetization. A single tap on a wire of soft iron will at once destroy any residual magnetism in it.

EFFECTS OF HEAT.

When iron is warmed, its magnetic properties undergo singular changes. Rise of temperature produces different effects at different stages of the magnetization, and the effects differ in different materials. In soft iron, in weak magnetic fields, the effect of raising the temperature is to produce an increase of permeability, which goes on until the specimen is at a full red heat, about 760° C., when it reaches the enormous value of 10,000, after which point it suddenly falls, and when the temperature of 780° C. (about) is reached, the iron ceases to be a magnetic body, its permeability at that temperature, and at all higher temperatures, not differing sensibly from that of air or vacuum. But, if placed in a very strong magnetic field, the action of raising the temperature produces a diminution of permeability, at first slight, then more rapid until the temperature of 780° C. is reached, when again all magnetism disappears. In steel the effect is curiously different. In both soft and hard steels, the effect, in a very weak magnetic field of about $\mathbf{H} = 0.2$, of raising the temperature is to increase the permeability, until it is heated to a point close up to 700° C., when it suddenly drops to zero. In a field of about $\mathbf{H} = 2$, its magnetization at the lower temperatures is greater, and the final drop sets in at a temperature considerably below 700°. In a strong field of $\mathbf{H} = 40$, the permeability drops steadily as the temperature rises. At high temperatures, too, all residual effects are smaller.

Fig. 100 shows the effects of temperature in modifying the magnetic curve of soft iron when under a magnetizing force of H = 4. It will be seen that the permeability increases gradually, as the temperature rises, from about 2500 to 3000, at a temperature of 630°, after which it drops to unity at a temperature of 785° C.

FIG. 100.



EFFECT OF HEAT ON PERMEABILITY OF SOFT IRON.

RESIDUAL MAGNETISM.

It is well known that several kinds of magnetic materials —lodestone, steel, particularly hardened steel, and hard sorts of iron—exhibit residual magnetism after having been subjected to magnetic forces. It is also known that closed circuits of soft iron—even of the very softest—will exhibit a considerable amount of residual magnetism so long as the circuit which they constitute is unbroken. A very simple illustration of this is afforded by any electromagnet possessing in its core and well-fitting armature a compact magnetic circuit. If it is excited by passing a current, which is then quietly turned off, the armature usually does not drop off, and may even require considerable force to detach it; but when once so detached will not again adhere, the residual magnetization not being permanent. In like manner a steel horse-shoe magnet, if magnetized powerfully while its keeper is across its poles, may become "supersaturated"; that is to say, magnetized to a higher degree of magnetization than it can retain in permanence, a portion of this residual magnetization disappearing the first time the keeper is removed.

All these residual phenomena are part of a wide subject of magnetic after-effects. Owing to causes presently to be discussed, magnetic forces, if sufficiently powerful, produce effects on the molecules of a magnetizable body which remain after the cause has passed away, with the result that if the causes change in a continuous manner the effects also change in a continuous manner, but suffer a retardation in phase, the cause lagging after the effect. This must not be confused with an alleged time-lag of magnetism to which many things have been supposed to be due which were really due to quite other things. The present considerations relate to retardations in phase rather than in time, and occur no matter whether the operations themselves are conducted quickly or slowly.

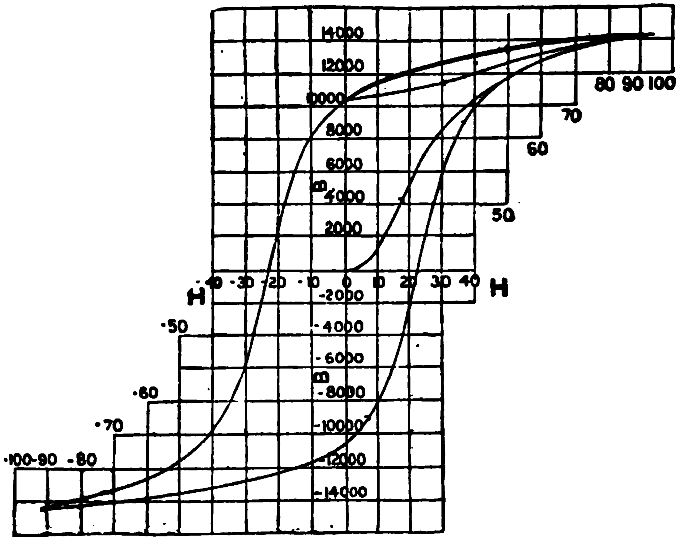
Reference to Fig. 92 will show that when the magnetizing force **H** is gradually increased from zero to a high value, and is then gradually decreased to zero, the resulting internal magnetization **B** first increases to a maximum, and then decreases, but does not come back to zero. The curve descending from the maximum does not coincide with the ascending curve. In fact, when the magnetizing force has been entirely removed there remained (in this specimen) a residual magnetization of about 47,000 lines to the sq. in., or about 7300 lines per sq. cm. It has been proposed to give the name of the *remanence* to the number of lines per sq. cm., that thus remain as the residual value of **B**. To remove this *remanence*, a negative magnetizing force must be applied. Suppose enough magnetizing force has been used, the curve will descend and cut the horizontal axis at a point to the left of the origin; and with greater negative magnetizing forces, the specimen will begin to be magnetized with magnetic lines running through it in the reversed direction. The particular value of the negative magnetizing force which is needed to bring the remanent magnetization to zero has been termed by Hopkinson *the coercive force.* In the specimen of wrought iron in question the coercive force (in C.G.S. measure) is about 2, or in sq. in. measure about 13. The force thus required to deprive any specimen of its remanent magnetization may be taken as a measure of the tendency of iron of this particular quality to retain permanent magnetism. Hard kinds of iron and steel always show more coercive force than soft kinds of iron. For example, whilst that of soft wrought iron is about 2, that of hard steel may be as much as 50.

[illegible]

HYSTERESIS.

Professor Ewing, who has particularly studied the residual effects exhibited by various qualities of iron and steel, has given the name of *hysteresis* to this tendency of the effects to lag, in phase, behind the causes that produce them. The appropriate mode of studying hysteresis is to subject the specimen to a complete cycle (or to a number of successive cycles) of magnetizing forces. For example, let the magnetizing force begin at zero, and increase to a high value (say to H = 200) and then decrease back to zero, then reverse and increase to a high negative value, and finally return to zero. Such a cycle is given in Fig. 101, which is taken from Ewing's

FIG. 101.



CYCLE OF MAGNETIC OPERATIONS ON ANNEALED STEEL WIRE.

researches, and relates to a series of experiments made with a piece of annealed steel pianoforte wire. The curve begins in the centre of the diagram, and as **H** is increased positively, the curve rises at first concavely to the right, then turns over, and when **H** = 9, **B** has risen to a little over 14,000. When **H** is then reduced back to zero the curve turns back on itself, but does not fall as fast as it previously rose, for when **H** is reduced to 20, **B** has gone down only to 12,000, and when **H** = 0 the remanence is about 10,500. If at this point **H** had been again increased to 90, **B** would have run up again to 14,000, as shown by the thin line. If, however, the magnetizing force is reversed, the curve descends to the left, and cuts the horizontal axis at — 24, which is therefore the value of the coercive force. On increasing the reversed magnetizing force to **H** = — 90, the reversed magnetization increases to the value **B** = — 14,000, or a little more. Then when these reversed magnetizing forces are reduced to zero, the curve returns towards the right, crossing the vertical axis at **B** = —10,500 (the negative remanence); and on re-reversing the magnetizing force it is found that when **H** = + 24, the magnetization is once more zero. After this point, increasing **H** causes the magnetization to run up very rapidly, not quite following its former track, but coming up as before to the apex, when **H** is raised to the same maximum of 90.

CYCLES OF MAGNETIZATION.

Such cycles of magnetization as that which has just been described, if carried out on any specimen of iron or steel, always yield curves that exhibit, like Fig. 48, an enclosed area. This fact has been shown by Warburg [1] and by Ewing [2] to possess a special significance, for the area inclosed is a measure of the work wasted in carrying the iron through a complete cycle of magnetizations. Just as the area traced out on the indicator-card of a steam engine is a measure of the heat transformed into useful work in the cycle of operations performed by the engine, so in this magnetic cycle the area enclosed by the curve is a measure of the work transformed into (useless) heat.[1]

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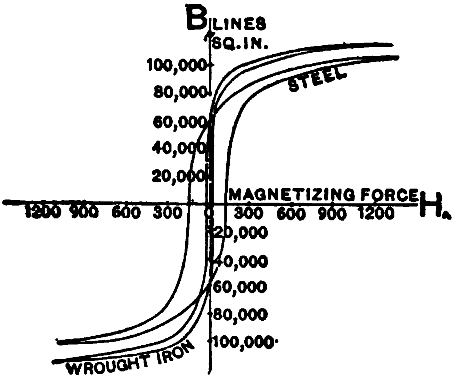
[1] *Wied. Ann.*, xiii. 141, 1881.

[2] *Proc. Roy. Soc.*, xxxi. 22, 1881; xxxiv. 39, 1884; and xxxv. 1, 1883; and *Phil. Trans.*, pt. ii. 523, 1885.

For the sake of comparison, a curve for wrought iron and one for steel are given side by side in Fig. 102. In all these cases the closed area represents the work which has been wasted or dissipated in subjecting the iron to these alternate magnetizing forces. In very soft iron, where the ascending and descending curves are close together, the enclosed area is small; and as a matter of fact, very little energy is dissipated in a cycle of magnetic operations. On the other hand, with hard iron, and particularly with steel, there is a great width between the curves, and there is great waste of energy.

FIG. 102.



HYSTERESIS IN WROUGHT IRON AND IN STEEL.

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[1] The proofs of these matters are as follows. In a magnetic field of strength **H** it will require **H** units of work to move a unit of magnetism along a length of 1 centimetre against the magnetizing forces. Hence, since there are 4π magnetic lines to each unit of magnetism, the work done in one complete cycle on a single cubic centimetre of the iron will be equal to $\frac{1}{4\pi}\int \mathbf{H}\, d\,\mathbf{B}$. If **H** and **B** are in C.G.S. units, the work will be given in ergs per cubic centimetre. Hence if this number is multiplied by the number of cycles per second and divided by 10^7, the result will express the number of watts of power wasted.

Hysteresis may be regarded as a sort of internal or molecular magnetic friction, by reason of which alternate magnetizations cause the iron to grow hot. Hence the importance of understanding this curious effect, in view of the construction of electromagnets that are to be used with rapidly alternating currents. The following figures of Table IX. give the number of watts (1 watt $= \frac{1}{746}$ of a horse-power) wasted by hysteresis in well-laminated soft wrought iron when subjected to a succession of rapid cycles of magnetization.

TABLE IX.—WASTE OF POWER BY HYSTERESIS.

$\mathbf{B}$	$\mathbf{B}_{''}$	Watts wasted per cubic foot at 10 cycles per second.	Watts wasted per cubic foot at 100 cycles per second.
4,000	25,800	40	400
5,000	32,250	47·5	575
6,000	38,700	75	750
7,000	45,150	92·5	925
8,000	51,600	111	1,110
10,000	64,500	156	1,560
12,000	77,400	206	2,060
14,000	90,300	202	2,620
16,000	103,200	324	3,240
17,000	109,650	394	3,940
18,000	116,100	487	4,870

It will be noted that the waste of energy increases as the magnetization is pushed higher and higher in a disproportionate degree, the waste when $\mathbf{B}$ is 18,000 being six times that when $\mathbf{B}$ is 6000. In the case of hard iron or of steel the heat waste would be far greater.

Hopkinson has made the remark that the area $\int \mathbf{H}\, d\mathbf{B}$ is approximately equal to a rectangle, the height of which is double the remanence, and the breadth of which is double the coercive force.

Ewing has given the following values of the energy wasted in a magnetic cycle of strong magnetization on various brands of iron and steel:—

TABLE X.—WASTE OF ENERGY BY HYSTERESIS.

Brand experimented upon.	Ergs per cubic centimetre lost in one complete cycle of magnetization.
Very soft annealed iron	9,300
Less soft ,, ,, ...	16,300
Hard drawn iron wire	60,000
Annealed steel wire	70,500
Glass hard steel wire	76,000
Pianoforte steel wire (ordinary state)	116,000
,, ,, ,, (annealed)	94,000
,, ,, ,, (glass hard)	117,000

These figures are surpassed by some of the brands examined by Hopkinson, who found that oil-hardened tungsten steel, the sort chosen for making permanent magnets because of its great coercive force, wasted no less than 216,864 ergs per cubic centimetre per cycle.

Ewing has shown that vibration tends to destroy residual effects. Also Dr. Finzi has found[1] that iron cores whilst traversed by an alternating electric current show no hysteresis, the ascending and descending curves of magnetization coinciding. There is also some evidence that with very rapid frequencies there is less work wasted per cycle than there would be in the same cycle performed slowly.

When an armature core is rotated in a strong magnetic field the magnetization of the iron is being continually carried through a cycle, but in a manner quite different from that in which it is carried when the magnetizing force is periodically reversed, as in the core of a transformer. Mordey has found[2] the losses by hysteresis to be somewhat smaller in the former case than in the latter.

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[1] *The Electrician*, xxvi. 72, April 3, 1891.

[2] See also Ewing, in *Electrician*, xxvii. 602, 1891.

MAGNETIC CREEPING.

Another kind of after-effect was discovered by Ewing, and named by him "viscous hysteresis." This is the name given to the gradual creeping up of the magnetization when a magnetic force is applied with absolute steadiness to a piece of iron. This gradual creeping up may go on for half-an-hour or more, and amount to several per cent. of the total magnetization. This is a true, but slow, magnetic lag, and must not be confounded either with the lag of phase discussed already under the name hysteresis, or with the apparent lag due to the retardation of the magnetizing current resulting from self-induction, or with the apparent lag observable in unlaminated iron cores due to eddy-currents circulating in the mass of the iron itself.

FORMULÆ FOR THE LAW OF THE ELECTROMAGNET.

Many attempts have been made to find a working formula to express the amount of magnetism which is produced in a given electromagnet by an exciting current of any particular value. Of these an elaborate account is given in the second and third editions of this book. As these are not founded on the principle of the magnetic circuit, they fail to account for all the various facts. And as they are not used in dynamo designing, they may be very briefly dismissed. They all amount to attempts to find a formula to represent algebraically the curves of magnetization such as that given in Fig. 92, p. 140.

The earliest suggestion of Lenz and Jacobi was a simple proportion between the exciting current (or ampere-turns) and the magnetism produced. This is equivalent to saying that the curve of magnetization is a straight line sloping upwards from the origin. Joule showed that this law was not true; that with sufficient magnetizing power saturation set in. Müller (followed by Von Waltenhofen, Kapp, and others) proposed an arc-tangent formula; suggesting that if the exciting current be represented by the length of a straight line drawn as a tangent to a circle, then the arc which it subtends will represent the amount of magnetism which results. This gives a saturation limit (for when the tangent is infinitely long the arc attains a finite value), but fails to represent the facts in the earlier stages of magnetization. Lamont, from theoretical considerations, proposed an exponential formula, from which he deduced an approximate expression

$$m = \frac{M\,k\,x}{1 + k\,x},$$

where m is the magnetism at any stage, M is its possible maximum value, x the exciting current, and k a constant depending on the units employed. This is equivalent to saying that the ratio of m to x (in other words, the permeability) is at all stages proportional to the defect of saturation $M - m$.

Frölich's Formula.—Lamont's formula was revived by Frölich,[1] and largely used in various forms by various writers, including the author of this book. Let us make the supposition that the magnetic flux $\mathbf{N}$ will have at complete saturation a maximum value $\bar{\mathbf{N}}$, and that the magnetizability of the magnet at any stage is proportional to the room left for magnetic lines, that is to $\bar{\mathbf{N}} - \mathbf{N}$. Now, writing S for the number of spirals and i for the current flowing in them, we get S i for the ampere-turns of exciting power, and $\mathbf{N} \div S\,i$ will be the ratio of magnetism to magnetizing power or magnetizability. We may then write

$$\frac{\mathbf{N}}{S\,i} = \frac{\bar{\mathbf{N}} - \mathbf{N}}{h},$$

where h is a constant of the particular electromagnet, the nature of which will be shown presently. By simple transformation this equation becomes

$$\mathbf{N} = \bar{\mathbf{N}}\,\frac{S\,i}{S\,i + h},$$

and it is clear that the meaning of h is that particular number of ampere-turns which will reduce the magnetizability to half its initial value, or will bring up the magnetism to half-saturation.

This number of ampere-turns the author named the *diacritical* number, and the number producing half-saturation he called the *diacritical* current. Dr. Frölich has independently made use of this conception, and has applied it in his formula for dynamos. The argument is his; the notation here used is, however, the author's. Writing $(\mathrm{S}\,i)'$ for the diacritical number of ampere-turns, we have $(\mathrm{S}\,i)' = h$, whence

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[1] *Elektrotechnische Zeitschrift*, pp. 90, 139, 170, 1881, and p. 73, 1882.

$$\mathbf{N} = \bar{\mathbf{N}} \frac{\mathrm{S}\,i}{\mathrm{S}\,i + (\mathrm{S}\,i)'}.$$

But, further, if S is known, then we may cancel it out and write simply

$$\mathbf{N} = \bar{\mathbf{N}} \frac{i}{i + i'},$$

where i' is the diacritical or half-saturating current. This very simple equation is approximately true for every electromagnet excited by a single current. Two observations made on any electromagnet will suffice to determine the two constants $\bar{\mathbf{N}}$ and i'. Further, if r be the resistance of the magnetizing coil, since $i\,r = e$ (the potential required to send the current i through the coil), we may obviously write the equation

$$\mathbf{N} = \bar{\mathbf{N}} \frac{e}{e + e'};$$

where e' is the diacritical difference of potential, namely, that difference of potential which, applied to the coil having resistance r and convolutions S, will half saturate the core. This last form is most convenient when calculations are to be made about shunt-dynamos, whilst the one preceding it is the more useful for series dynamos.

None of these formulæ account for the phenomenon alluded to on p. 141, which is observed in the magnetization of many pieces of iron and steel (and especially in closed rings of iron and steel), namely, that there is an apparent increase in the permeability after a certain early stage in the magnetization has been reached. Lenz first noticed this in 1854. Wiedemann, Dub, Stoletow, Rowland, Chwolson, Bosanquet, and Siemens have all investigated the matter; Rowland, Bosanquet, and Ewing in particular having given careful numerical determinations of the variations of permeability under varying degrees of ascending magnetization. The researches of Chwolson and Siemens seem, however, to show that the apparent increase of the permeability is due to the want of homogeneity in the iron, and to the presence of a certain proportion of particles having the properties of hard steel and requiring a certain minimum of magnetizing force to be applied before they become sensibly magnetized, there being an apparent more rapid growth of the magnetism when this stage is reached. According to this view, the permeability due to temporary magnetism begins by being a maximum, and diminishes as the magnetizing force is increased; whilst the permeability due to permanent magnetism is zero at first and until a certain stage, when it rises rapidly to a maximum of its own, and thereafter dies gradually away. That which Stoletow, Rowland, and Bosanquet have measured with so much care, is the sum of these two effects. Siemens makes the valuable remark that the harder the piece of iron or steel, the later is the stage at which this apparent maximum of magnetic permeability is observed.

The result of this superposition of effects in the dynamo machine is that when the "characteristic" is taken *with ascending strengths of current*, there may be observed—and this is not marked, save in dynamos in which the iron constitutes very nearly a closed circuit on itself—a concavity, as explained on p. 141, in the first part of the characteristic, which is often taken as an oblique straight line. But if the characteristic is taken with descending strengths of current, no such concavity is observed, the magnetism of the field-magnets, and also the electromotive-force, having values considerably higher, for the same value of exciting current, than in the ascending curve. The presence of permanent magnetism in the core is therefore detrimental to the steadiness of the field. Even with the softest Swedish iron, differences may be observed in the electromotive-force, with the same speed and the same exciting current, before and after the exciting current has been increased to a high degree. For this reason the approximate formula known as Frölich's is good enough as a first approximation, though it does not take into account the presence of the apparent increase in permeability or the retardation of the apparent maximum in cores having greater coercivity. For further information on the differences between the ascending and descending curves of magnetism, the reader is referred to the researches of Warburg, Ewing, and Hopkinson, or to the summary of them in the earlier part of this chapter.

Ewing's Molecular Theory of Magnetism.—Ewing's recent theory of induced magnetism accounts for the observed effects, but does not lend itself to any simple formula. He has shown[1] that all the phenomena of hysteresis, remanence, influence of stress, heat, and the like, can be explained on the supposition that the individual molecules which act as elementary magnets are subjected to mutual directive actions. He supposes, with Weber, that the act of magnetization consists in turning these molecules into alignment with the magnetic force, complete saturation being attained when all have been completely turned round. The apparent increase in permeability when a certain value in the magnetizing force has been attained he explains by showing that at a certain stage an instability will be set up, when, with any small increase in the magnetizing force, a large number of the molecular magnets will suddenly swing round into new positions. He has further shown that in a model constructed with a large number of small pivoted magnets exercising mutual influences, the magnetic properties can be explained by considering the configurations assumed by the system under the joint action of external and internal magnetic forces. Mr. A. Hoopes[1] has verified Ewing's theory by studying the magnetic properties of such an assemblage of small pivoted needles acting as a whole, and finds the system to exhibit instabilities and hysteresial effects like those of masses of iron.

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[1] *Proc. Roy. Soc.*, June 19, 1890; also *The Electrician*, xxv. 514, 541.

Magnetic Reluctivity.—The reciprocal of magnetic permeability has been called reluctivity by Kennelly.[2] If this quantity is plotted out against **H**, the curve so plotted is nearly a straight line, or the reluctivity is a linear function of **H** of the form of $a + b\,\mathbf{H}$. This oblique line is simply the reciprocal to the hyperbolic curves found by Stoletow and others for μ and **H**. As pointed out by Fleming,[3] and more recently by Kennelly, the circumstance that the reluctivity is found so nearly a linear function of **H** is a justification of the empirical formula of Frölich given above on p. 166.

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[1] *Electrical World*, xvii. 358, 1891.

[2] *Ibid.*, xviii. 350, 1891.

[3] *Journal Inst. Electrical Engineers* xv. 570, 1886.

CHAPTER VII.

THE MAGNETIC CIRCUIT.

THE most important recent step in the practical treatment of magnetic problems has been the use of the conception of the magnetic circuit. The principle is briefly as follows: that *a minimum expenditure of magnetizing power will give a maximum of effective magnetism when the iron parts of the dynamo, the cores of the field-magnets, the yoke, the pole-pieces, and the core of the armature, are so disposed that they constitute together a magnetic circuit having a minimum magnetic reluctance.*

It is no novelty to regard the magnetism of a magnet as something that traverses or circulates around a definite path, flowing more freely through such substances as iron, than through other relatively non-magnetic materials. Analogies between the flow of electricity in an electrically-conducting circuit, and the passage of magnetic lines of force through circuits possessing magnetic conductivity are to be found abundantly in the literature of the science. So far back as 1821, Cumming[1] experimented on magnetic conductivity. The idea of a magnetic circuit was more or less familiar to Ritchie,[2] Sturgeon,[3] Dove,[4] Dub,[5] and De la Rive[6] the last-named of whom explicitly uses the phrase "a closed magnetic circuit." Joule[7] found the maximum power of an electromagnet to be proportional to "the least sectional area of the entire magnetic circuit," and he considered the resistance to induction as proportional to the length of the magnetic circuit. Faraday[1] considered that he had *proved* that each magnetic line of force constitutes a closed curve; that the path of these closed curves depended on the magnetic conductivity of the masses disposed in proximity; that the lines of magnetic force were strictly analogous to the lines of electric flow in an electric circuit. He spoke of a magnet surrounded by air being like unto a voltaic battery immersed in water or other electrolyte. He even saw the existence of a power, analogous to that of electromotive-force in electric circuits, though the name *magnetomotive-force* is of more recent origin. The same idea is more or less implicitly recognized in the latter half of the magnetic papers in Sir William Thomson's collected volume on Electrostatics and Magnetism. The notion of magnetic conductivity is to be found in Maxwell's great treatise (vol. ii. p. 51), but is only briefly mentioned. Rowland[2] in 1873 expressly adopted the reasoning and language of Faraday's method in the working out of some new results on magnetic permeability, and pointed out that the flow of magnetic lines of force through a bar could be subjected to exact calculation; the elementary law, he says, "is similar to the law of Ohm." Writing R for the "resistance to lines of force," M for "magnetizing force of helix," and Q for number of "lines of force in a bar at any point," he wrote, for a particular case (a ring-magnet, having therefore a closed magnetic circuit), the equation,

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[1] *Camb. Phil. Trans.*, April 2, 1821.

[2] *Phil. Mag.*, series iii. vol. iii. 122.

[3] *Ann. of Electr.*, xii. 217.

[4] *Pogg. Ann.*, xxix. 462, 1833. See also *Pogg. Ann.*, xliii. 517, 1838.

[5] *Dub. Elektromagnetismus*, p. 401 (ed. 1816); and *Pogg. Ann.*, xc. 440, 1853.

[6] De la Rive. *Treatise on Electricity* (Walker's translation), i. 292.

[7] *Ann. of Electr.*, iv. 59, 1839; v. 195, 1841; and *Scientific Papers*, pp. 8, 34, 35, 36.

$$Q = \frac{M}{R};$$

an equation for magnetic circuits which every electrician will recognize as being precisely like Ohm's law. He applied the calculations to determine the permeability of certain specimens of iron, steel, and nickel. In 1882,[1] and again in 1883, Mr. R. H. M. Bosanquet[2] brought out at greater length a similar argument, employing the extremely apt term "Magnetomotive Force," to connote the force tending to drive the magnetic lines of induction through the "magnetic resistance" or "reluctance" of the circuit. In these papers the calculations are reduced to a system, and deal not only with the specific properties of iron, but with problems arising out of the shape of the iron. Bosanquet shows how to calculate the several reluctances of the separate parts of the circuit, and then add them together to obtain the total reluctance of the magnetic circuit.

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[1] *Experimental Researches*, vol. iii. arts. 3117, 3228, 3230, 3260, 3271, 3276, 3294, and 3361.

[2] *Phil. Mag.*, series iv. vol. xlvi. August, 1873. "On Magnetic Permeability and the Maximum of Magnetism of Iron, Steel, and Nickel."

Prior to this, however, the principle of the magnetic circuit had been seized upon by Lord Elphinstone and Mr. Vincent, who proposed to apply it in the construction of dynamo-electric machines. On two occasions[3] they communicated to the Royal Society the results of experiments to show that the same exciting current would evoke a larger amount of magnetism in a given iron structure, if that iron structure formed a closed magnetic circuit, than if it were otherwise disposed. They embodied their ideas in a form of dynamo,[4] which however, on account of mechanical difficulties, did not establish itself as a permanent type of machine. The work of Lord Elphinstone and Mr. Vincent was not however lost, for the principle thus introduced by them into the construction of dynamos took root and bore fruit. In June 1884, the author of this book, in the preface to its first edition, writing on the imperfection of our knowledge of the laws of magnetic induction wrote: *We want some new philosopher to do for the magnetic circuit what Dr. Ohm did for the voltaic circuit fifty years ago.* In the autumn of the same year, at the conference of electricians at Philadelphia, Professor Rowland read a paper[1] in which he proposed a formula for the number of magnetic lines in a field-magnet. He found the product of the existing current into the number of spirals in which it circulated (*i. e.* the ampere-turns) and divided this by a complex expression, representing the *resistance* to the flux of the magnetic lines in the air and in the iron; allowing something for the tendency of some of the magnetic lines to escape.

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[1] *Proc. Roy. Soc.*, xxxiv. 445, December, 1882.

[2] *Phil. Mag.*, series v. vol. xv. 205, March, 1883. "On Magneto-motive Force." Also *ibid.*, vol. xix. February, 1885; and *Proc. Roy. Soc.*, No. 223, 1883. See also *Electrician*, xiv. 291, February 14th, 1885.

[3] *Proc. Roy. Soc.*, xxix. 292, 1879; and xxx. 287, 1880. See *Electrical Review*, viii. 134, 1880.

[4] Specifications of Patents, 332 of 1879, and 2893 of 1880. See also the former editions of this work.

An important development of the foregoing ideas was made by Mr. Gisbert Kapp, in a series of papers contributed to the *Electrician*[2] between February, 1885, and April, 1886, in which the question of the design of dynamos was discussed from this point of view, with many illustrations touching the forms of field-magnets, and some calculations and formulæ of great interest. While these papers were in progress, the author was preparing for the press the second edition of this work, and drew up the sketches of the magnetic circuits of a large number of types of dynamo machines, that are given in a collected form in Fig. 119. Three months later a sheet of figures, very closely resembling these, was given by Mr. Kapp, who had prepared them in entire independence, in an important paper[3] which he communicated on Nov. 24th, 1885, to the Institution of Civil Engineers. In this paper Kapp adopted a new unit of lines of force, 6000 times greater than the C.G.S. unit, the reason of this being that he preferred to have to divide by 10^6 instead of 10^8, and to speak of the number of revolutions per minute instead of the number of revolutions per second. Using Z for the number of magnetic lines, in Kapp units (where $Z = \mathbf{N}$ of our notation C.G.S. units $\div$ 6000,) and n for revolutions per minute, Kapp puts,

$$\mathbf{E}\ (\text{volts in armature}) = Z \cdot Nt \cdot n \cdot 10^6;$$

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[1] Report of the Electrical Conference at Philadelphia in 1884, p. 77. See also *Electrical Review*, xv. 368, 1884: and *Electrician*, xiii. 536, 1884.

[2] *Electrician*, xiv. 159, 307, 347, 390, 431, 511; xv. 23, 190, 250; xvi. 7, 406.

[3] *Proc. Inst. Civil Engineers*, lxxxiii. (1885–6), pt. 1, "Modern Continuous-Current Dynamo-Electric Machines and their Engines."

the symbol Nt standing for number of turns of wire around the armature as counted all round the periphery (the same for which symbol C is used in this book hereafter). Kapp then further wrote for the magnetic circuit the formula

$$Z = \frac{P}{R_a + R_A + R_F},$$

where P is the exciting power in ampere-turns, R_a the magnetic reluctance of the air-space, R_A that of the armature core, R_F that of the field-magnets. Now let δ represent distance across the span between armature core and polar surface, b breadth of armature as measured parallel to axis, λ the length of arc embraced by polar surface, so that $\lambda\, b$ is the polar area out of which magnetic lines issue, a radial depth of armature core, so that $a\, b$ is area of section of armature core (space actually occupied by iron only being reckoned), A B area of field-magnet core, l length of magnetic circuit within armature, L ditto in field-magnet; all the dimensions being measured in inches or square inches respectively. Then, in case of an ordinary single magnetic circuit, Kapp writes

$$R_a = 1440\frac{2\,\delta}{\lambda\, b},$$

$$R_A = \frac{l}{a\, b},$$

$$R_F = 2\,\frac{L}{A\,B}.$$

The coefficient 1440 arises from the peculiar units, inch for length, minute for time, and 6000 C.G.S. for unit of magnetic lines; and this number may be taken as representing in this mixed system of units the specific magnetic reluctance of air. The coefficient 2 relates to the specific reluctance of wrought iron or charcoal iron; the figure 3 must be substituted in case of cast-iron magnets.[1] Moreover, on account of magnetic leakage in the formula for Z, 0·8 P has to be used instead of P. In the debate on this paper, Prof. G. Forbes gave a further modification of the formula. Still, more recently Mr. Kapp[1] has returned to the subject, and has given an empirical rule for calculating the variations of the magnetic reluctance of the iron at the various stages of magnetism.

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[1] These formulæ are explained in *Electrician*, xv. 250, August 14th, 1885.

In May, 1886, Drs. John and Edward Hopkinson communicated to the Royal Society[2] a very complete and elegant investigation of the problem of magnetic circuits, for the purpose of finding a suitable and accurate expression for the electromotive-force of the dynamo in terms of the magnetizing current; the most important part of their investigation being directed to constructing the curve characteristic of magnetization of the dynamo from the ordinary laws of magnetism and from the known properties of iron. The process in its first approximation resembles the process adopted by Kapp; but it stands alone in an important respect, namely, that its authors plot a separate characteristic curve for the relation between the magnetizing force and the induction for each separate part of the magnetic circuit, and then sum up the separate curves so as to obtain a final resultant characteristic curve. This is done first on the assumption that there is no magnetic leakage, and with other assumptions for the sake of simplifications. After a first approximation has thus been obtained, the theoretical result is compared with the actual result of experiment, thereby affording a means of estimating the corrections that must be introduced, the magnitude of the correcting factors being thus known, and the theory perfected to a second degree of approximation.

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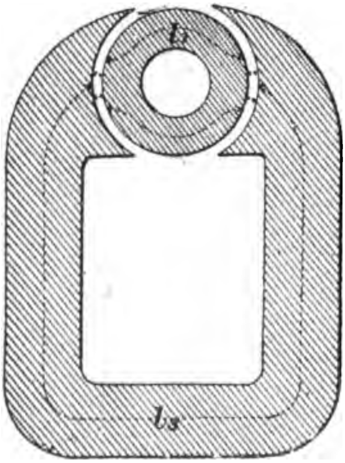
[1] *Journal Soc. Telegraph Engineers and Electricians*, xv. 524–529, November 11th, 1886. "On the Predetermination of the Characteristics of Dynamos"; a very valuable paper marred by mixed units. Those who wish to study examples of this mode of calculating, will find some examples in a paper communicated by Professor Jamieson in Jan., 1889 to the *Institution of Engineers and Shipbuilders in Scotland*; vide *Electrician*, March 1, 1889.

[2] *Phil. Trans.*, part i. p. 331, 1886. "Dynamo-Electric Machinery." This important paper is reprinted *in extenso*, but without the plates, in *Electrical Review*, xviii. 471, November 12th, 1886, and subsequent numbers. See also *Electrician*, xviii. 39, 63, 86, and 175, in issues of November 19th, November 26th, December 3rd, and December 31st, 1886, where the figures of the plates are printed in the text.

In describing the Hopkinsons' formulæ, we shall employ not their notation, but the same that is adopted in the rest of this book (see p. 208).

Let **N** be the whole magnetic flux through the armature, that is to say, the total number of lines of magnetic force that pass into the armature core on one side and out of it at the other. Assume (to simplify matters) that there is no waste or leakage of magnetic lines. Then remember that the magneto-motive force (or line-integral of the magnetizing[1] forces acting round the circuit) is equal to $4\pi S i \div 10$, where S is the number of turns of wire and i the amperes. Now the magnetic reluctance of any magnectic conductor is proportional to its length and inversely proportional to its sectional area, and also inversely proportional to its permeability. Suppose then, as shown in Fig. 103, that the magnetic circuit of the dynamo is made up simply of three parts; an iron armature-core, the two air-gaps, and the iron field-magnets, then the iron armature-core, in which the average length of path for the magnetic lines is l_1, the average sectional area A_1 and of permeability μ_1, will have a magnetic reluctance equal to $\frac{l_1}{\mu_1 A_1}$. Similarly for the two gaps: if the length of path across each, from iron to iron, be called l_2, and the area of either polar surfaces be A_2, and the

FIG. 103.



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[1] See Maxwell's *Electricity and Magnetism*, vol. ii. art. 499; or S. P. Thompson's *Elementary Lessons on Electricity and Magnetism* (edition of 1887, pp. 291-296.) See also p. 125 of this book.

permeability of the matter that occupies the gaps be called μ_2, then the magnetic reluctance these two offer to the magnetic flux will be $2\frac{l_2}{\mu_2 A_2}$; or, remembering that for air, copper, and all ordinary non-magnetic substances $\mu = 1$, this may be written simply $2\frac{l_2}{A_2}$. Similarly for the iron field-magnet; writing l_3 for length of path through the iron from pole to pole, A_3 for sectional area (supposed to be equal throughout), and μ_3 for permeability, the magnetic reluctance will be $\frac{l_3}{\mu_3 A_3}$. Adding these three reluctances together, we get as the total reluctance of the magnetic circuit the value

$$\frac{l_1}{\mu_1 A_1} + 2\frac{l_2}{A_2} + \frac{l_3}{\mu_3 A_3}.$$

Whence we may immediately write down as the appropriate formula,

$$\text{total number of magnetic lines} = \frac{\text{magneto motive-force}}{\text{magnetic reluctance}}; \text{ or}$$

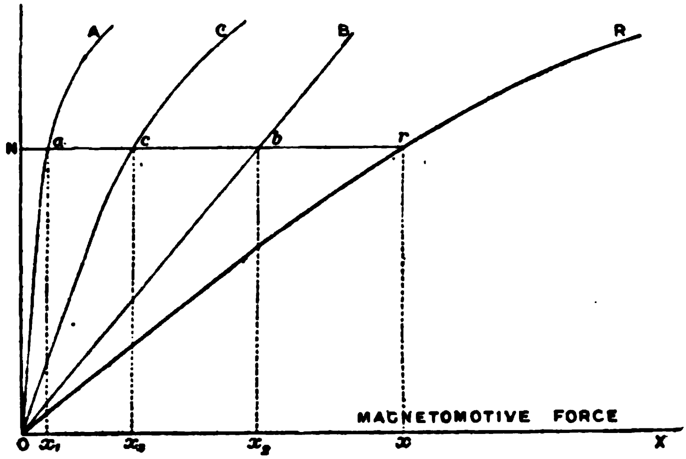
$$\mathrm{N} = \frac{4\pi S i}{10\left\{\frac{l_1}{\mu_1 A_1} + 2\frac{l_2}{A_2} + \frac{l_3}{\mu_3 A_3}\right\}}$$

As a matter of fact, the Hopkinsons stated their formula a little more generally. In the first place, instead of adding up the separate magnetic reluctance, they calculated the magnetic forces needed in the separate parts and then added these together. In the second place, instead of assuming the existence of μ for the different parts, they contented themselves with saying that the magnetic induction in each part must be some function of the magnetic force acting in that part. Now, if there be a flux of **N** magnetic lines passing through sectional area A square centimetres, the number of lines per square centimetre, which we call the "induction" **B** will be equal to $\frac{\mathrm{N}}{\mathrm{A}}$. Accordingly, we may write for the magnetomotive-force, acting in the armature part of the magnetic circuit $f\left(\frac{N}{A_1}\right)\times l_1$, which "function" may be examined and plotted out as a curve. In fact, the curves of magnetization, such as are given on p. 132, are nothing else than curves which show the relation between the magnetizing forces and the amount of magnetism they induce. There will be a similar expression $f\left(\frac{N}{A_3}\right)\times l_3$ for the magnetomotive-force that acts in the field-magnet part, whilst for the gaps the magnetomotive-force is simply $\frac{N}{A_2}\times 2\,l_2$; for the function for air $= 1$. Now, if we know the separate amounts of magnetizing force required to produce these magnetic inductions in the separate parts, it is clear that the whole or integral magnetizing force in question will be got by adding them together, giving

$$l_1 f\left(\frac{N}{A_1}\right) + 2\,l_2\,\frac{N}{A_2} + l_3 f\left(\frac{N}{A_3}\right) = 4\,\pi\,Si \div 10.$$

There are three advantages in this mode of stating the matter: (1) The use of the function of which the value is to be found by reference to a curve or tabulated set of observations (such as those given in Figs. 92, 93, and 95, or statistically on p. 146), instead of merely using the symbol μ, makes the expression more general; (2) the separate terms being differently affected by the leakage of the magnetic lines, it is easy to apply a correction to any one of them separately; (3) this form of the formula is convenient, in the case of a given iron carcase, to calculate the number of ampere-turns required to excite the working quality of magnetism. For we have now three terms, the first telling us how many ampere turns of excitation are required to drive **N** magnetic lines through the reluctance of the armature core, the second telling how many are required to drive **N** lines through the gap-space, and the third telling how many are required to drive **N** lines through the iron cores of the field-magnets. In a well-designed dynamo the second term is numerically the most important of the three, and it is not complicated by any question of saturation; for in air the magnetic induction is always proportional to the inducing magnetic force. To represent this graphically upon a diagram (Fig. 104), plot out as ordinates the numbers of magnetic lines that are forced round the circuit, and plot horizontally as abscissæ the corresponding values of the requisite magnetomotive-force $4 \pi S i \div 10$. For the second term, which relates to the gaps, the relation will be represented simply by a sloping line such as O B. For example the number of magnetic lines N that are to be forced across the gap between the armature and field-magnets being represented to scale by the length of the line O N, the corresponding value of $2 l_2 \frac{N}{A_2}$, which is the corresponding part of the magnetomotive-force, when plotted out on the horizontal scale as O x_2, gives b as a point through which the line passes. Similarly we may construct a curve to represent the first term by the curve A; for if we know from experiments made on iron of the same kind as is used in the armature core the values of the function f (or, what comes to the same thing, the various corresponding values of μ_1) we can calculate the

Fig. 104.



value of the quantity $l_1 f\left(\frac{N}{A_1}\right)$ and set it off as O x_1, giving *a* as a point on this curve. Similarly the curve C is calculated point by point for the third term, by using knowledge derived from experiments made on iron of the same kind as is used in the field-magnets. Now, from these three curves A, B, and C, which represent the various values of the three terms on the left-hand side of the equation, we can at once get the resultant curve that is characteristic of the whole magnetic circuit of the dynamo. For if we draw a level line across at the point N, we know that the three overlapping lengths N *a*, N *b*, N *c*, (which are respectively equal to the three lengths O x_1, O x_2, and O x_3,) represent the three corresponding separate parts of the magnetomotive-force. Adding these three lengths together, we get O *x* or N *r* as the total magnetomotive-force; and this gives us *r* as a point on the resultant curve, which we may complete by finding other points in a similar way and sweeping the curved line O R through them. Having in this way built up a curve characteristic of the magnetization, the Hopkinsons then proceeded to correct it by considering the leakage. They found that in the dynamo experimented upon (an Edison-Hopkinson) only about three-fourths of the magnetic lines created in the field-magnet actually passed through the armature core, the rest leaking across either between the pole-pieces through the air or the bed-plate. or else turning back from the pole-pieces to the yoke at the top. Experiment gave the ratio of the magnetic flux at a point half-way up the upright iron cores to the flux through the armature as 1·32. That is to say, in this particular type of machine, to force 100 lines through the armature core one will have to excite 132 in the field-magnet cores, and therefore will have to put on more magnetomotive-force accordingly. Let the symbol v stand[1] for this ratio. Then in the particular dynamo experimented on there was a yoke at the top through which the length of (curved) path was l_4, and which had cross-section A_4. There were also solid pole-pieces, for which the corresponding quantities were called l_5 and A_5. Inserting these additional matters into the equation, it now becomes

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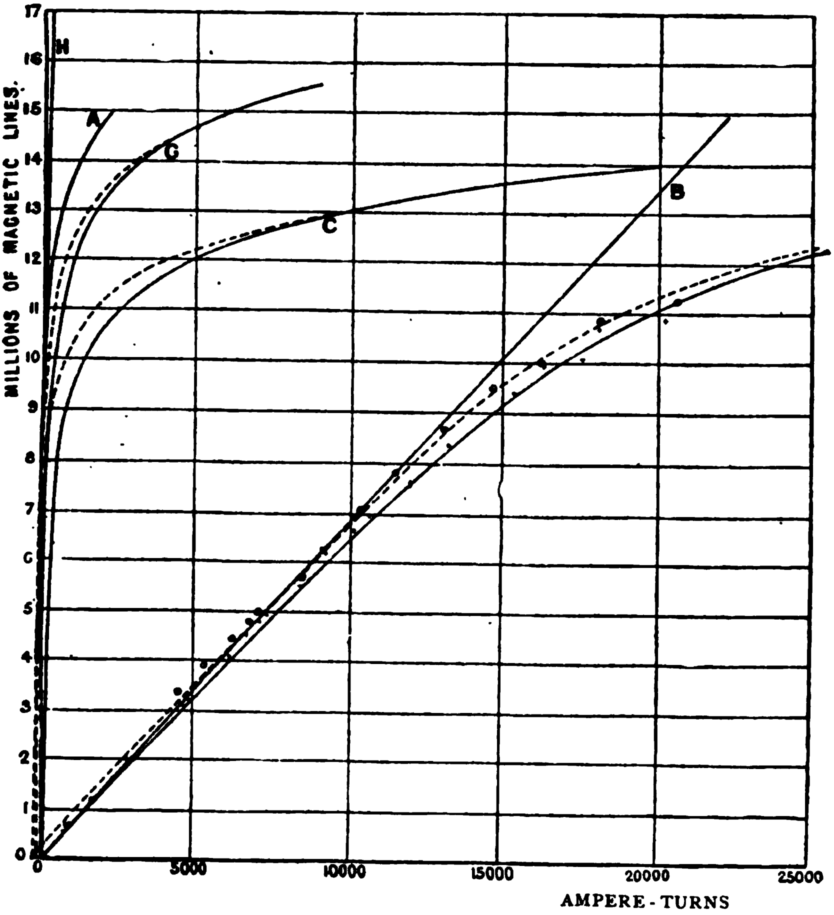
[1] It can be determined experimentally, or calculated as hereafter shown.

$$l_1 f\left(\frac{N}{A_1}\right) + 2 l_2 \frac{N}{A_2} + l_3 f\left(\frac{vN}{A_3}\right) + l_4 f\left(\frac{vN}{A_4}\right) + 2 l_5 f\left(\frac{N}{A_5}\right)$$
$$= 4 \pi S i \div 10.$$

Fig. 105.



There are now five terms to be calculated giving five curves. Moreover, as is well known, with descending magnetizing forces the curve of magnetization is different from the curve with ascending magnetizing forces. Fig. 105, which is taken from the Hopkinsons' paper, shows how they plotted out both for ascending and descending magnetizations the five curves. Of these, A relates to the armature, B to the two interstitial gaps, C to the field-magnet cores, G to the yoke, and H to the two pole-pieces. The resultant ascending and descending curves are also shown. They agree remarkably well with the crosses and points which were plotted out from actual experiment. The dotted curves and the crosses surrounded with circles relate to descending magnetization. The student should not fail to consult the original paper, which though brief is full of important matter, and in which applications of this method to two dynamos of different types are given.

The magnetization curves, Figs. 95 and 96, pp. 144 and 145, being the same used by the Hopkinsons, may be used by the student. The ordinates being values of $\mathbf{N} \div A$, the abscissæ give the corresponding values of $f\,(\mathbf{N} \div A)$ or of $\frac{1}{\mu}\,(\mathbf{N} \div A)$.

Example.—In one particular machine examined by the Hopkinsons, the same Edison-Hopkinson dynamo described on p. 521, Figs. 351, 352, the following were the dimensions:—l_1 13 centimetres, l_2 1·5 centimetre, l_3 91·4 centimetres, l_4 49 centimetres, l_5 11 centimetres; A_1 810 square centimetres; A_2 on core 1410, on polar face 1513 square centimetres, or, allowing for spreading, say 1600 square centimetres; A_3 930 square centimetres; A_4 1120 square centimetres; A_5 1230 square centimetres; $v = 1{\cdot}32$; $\mathbf{N}$, when the machine was at full work, a little over 10,850,000; $S = 3260$; $r_s = 16{\cdot}93$.

LEAKAGE OF MAGNETIC LINES.

In all dynamos there is some magnetic leakage. That is to say, in all dynamos, of the magnetic lines which are excited in the field-magnet some fail to pass through the armature, and leak out sideways, constituting a *stray field*. In some cases more than half the magnetic lines are wasted in leakage.

The ratio of total field to useful field is known as the coefficient of leakage v. Esson [1] has given the following values in sundry machines.

STRAY FIELD IN DIFFERENT DYNAMOS

Name of Machine.	Field.	Armature.	Remarks.	Value of v.
Edison-Hopkinson..	Single Magnet, 2-pole	Drum	Poles next bed-plate	1·32
Siemens	Single Magnet, 2-pole	Drum	Yoke next bed-plate	1·30
Phœnix	Single Magnet, 2-pole (Fig. 8)	Long Ring	Yoke next bed-plate	1·32
Phœnix	Double Magnet, 2-pole (Fig. 3)	Long Ring	Horizontal	1·40
Manchester	Double Magnet, 2-pole	Long Ring	Bed and one pole cast together	1·49
Victoria	Double Magnet, 4-pole	Short Ring	Ordinary pattern	1·40
Ferranti	Double Magnet, multipolar	Coreless Disk	Ordinary pattern (alternating)	2·00

The nature of leakage may be better comprehended by remembering that air is really a magnetic conductor, though less permeable than iron. The stray field around a dynamo may be explored by moving a compass-needle about in it; and the intensity at various points may be estimated by an exploring-coil connected to a suitable galvanometer. Fig. 106 depicts the general direction of the magnetic lines that leak from an Edison-Hopkinson dynamo. It will be noted that leakage takes place in other ways than from pole to pole. There will be a tendency to leak between any two points of the magnetic systems between which there is a difference of magnetic potential. Thus, there is a tendency for magnetic lines to leak from the pole-pieces to the yoke at the top. The cast-iron bed-plate being in proximity to the two poles (where the difference of magnetic potential is greatest) promotes leakage through itself, even though the machine is mounted on a zinc footstep.

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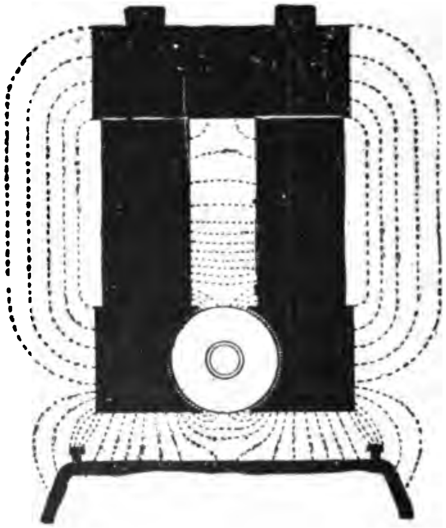
[1] *Journal Inst. Electrical Engineers*, xix. 122, 1890.

Many machines have been examined as to their magnetic leakage by Carl Hering,[1] who also has given drawings of them. An extraordinary case was found to be afforded by the stray field of the Thomson-Houston arc lighting dynamo (Fig. 307, p. 465). The reader should also refer to some experiments by Carhart[2] and to some by Trotter.[3]

FIG. 106.



STRAY FIELD OF AN EDISON-HOPKINSON DYNAMO.

It is evident that the leakage coefficient cannot be constant in a given machine, for the amount of leakage depends on the relative permeance of the path through the armature core and of the stray paths outside. Now the permeability of air is a constant, whilst that of the iron cores decreases as the degree of saturation is raised; so that the leakage increases with higher excitation. Also when a large current is drawn from the armature, the demagnetizing reaction of the armature current directly promotes leakage, as it raises an opposing magnetomotive-force in the direct path of the magnetic lines. Moreover, since leakage is not confined to actual polar ends, but takes place more or less all over a magnet, it is clear that what we call the coefficient of leakage is only a sort of average quantity.

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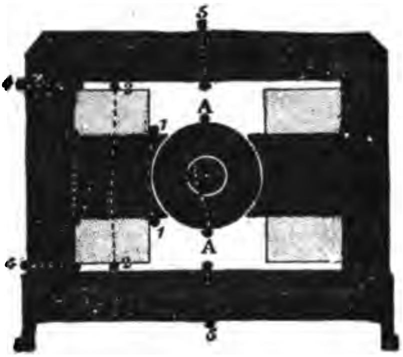
[1] *Electrical Review*, xxi. 186 and 205, 1887.

[2] *Electrical Review*, xxv. 286; and *Electrician*, xxiii. 644, 1889.

[3] *Journal Inst. Electrical Engineers*, xix. 243, 1890.

By experiment we may determine the actual value of the leakage ratio in various parts. Drs. J. and E. Hopkinson did this for a "Manchester" dynamo,[1] using exploring coils placed around the field-magnet of the dynamo in various positions. The number of magnetic lines which were thus enclosed was ascertained by suddenly cutting off the exciting current and noticing the resulting induction current in a suitable galvanometer. A still more complete examination was made by Lahmeyer[2] on an ironclad dynamo (Fig. 107). In this case six separate exploring coils, each having the same number of turns, were used. That surrounding the armature, enclosing the useful field, is called A, the others being numbered. The deflexions obtained are given in column 2 of the following table. The maximum flux was found at 3. Taking this number as 100, the percentages of leakage at the coils are given in column 3. In column 4 are given the various fluxes, taking that through A as 100, and in column 5 the values of v at the various parts. It is clear that the yoke parts were of insufficient thickness.

FIG. 107.



EXPLORING THE MAGNETIC LEAKAGE OF A DYNAMO.

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[1] See their paper in *Phil. Trans.*, Part i. p. 331, 1886 ; and *Electrician*, xviii. pp. 39, 63, 86, and 175, Nov. and Dec. 1886.

[2] *Elektrotechnische Zeitschrift*, ix. 283, 1887.

A	780	10·9	100	1
I.	788·5	10·1	101	1·01
II.	861	1·6	110	1·10
III.	876	0	112	1·12
IV.	850	3·0	109	1·09
V.	749	14·5	96	0·96

In the case of the Edison-Hopkinson dynamo, the Hopkinsons give 1·32 for *v*, this being the ratio observed between the throw when the exploring coil was placed half way up the magnet limbs and when it was placed around the armature. There is no doubt that the number is too small. If the exploring coil had been placed higher up, and if the armature had been excited so as to exert a demagnetizing action, the leakage coefficient would have been found to be at least 1·4.

CALCULATION OF LEAKAGES.

It is possible to predetermine, from the working-drawings of a dynamo before it is built, the probable amount of leakage. Calculations of the leakage are based upon the principle that where a circuit offers alternative paths, the magnetic flux will divide itself between the paths in the proportion of their relative facility for flow, exactly as an electric current divides where there are alternative conducting paths. In fact, the law of shunts has been found to hold good for magnetic lines. The reader should consult the researches of Ayrton and Perry[1] on this point. It follows that along any branched path the joint *permeance*[2] (or magnetic conductance) will be the sum of the permeances of the separate paths. Hence, if the permeances of the separate paths of the useful and waste magnetic fluxes of a dynamo are known, the coefficient of allowance for leakage, v, can be calculated, it being the ratio of the total flux to the useful flux. Call the useful flux u and the waste flux w; then

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[1] *Journal Soc. Teleg. Engineers and Electricians.* p. 530, 1886.

[2] *Permeance* is of course the reciprocal of magnetic reluctance; just as in electricity conductance is the reciprocal of electric resistance.

$$v = \frac{u + w}{u}$$

But each of these is a complex quantity; therefore the more complete formula is

$$v = \frac{u_1 + u_2 + u_3 + \ . \ . \ . \ . + w_1 + w_2 + w_3 + \ . \ . \ .}{u_1 + u_2 + u_3 + \ . \ . \ . \ .}$$

In order to determine the separate permeances along the various leakage paths, we must resort to some useful rules or lemmas originally suggested by Professor Forbes,[1] which consist in certain approximate integrations. For the convenience of British engineers the values have been recalculated into inch measures instead of centimetre measures, and other rules have been added.

Rule I.—Permeance between two parallel areas facing one another. Assume (Fig. 108) that the magnetic lines are straight and equally distributed over the surfaces: then,

$$\text{Permeance} = 3{\cdot}1918 \times \text{mean area (square inches)} \div \text{distance (inches) between them}$$
$$= 1{\cdot}596 \times (A_1'' + A_2'') \div d.''$$

FIG. 108.

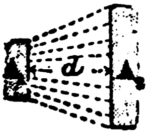
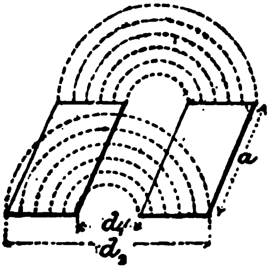


FIG. 109.



Rule II.—Permeance between two equal adjacent rectangular areas lying in one plane. Assuming (Fig. 109) lines of leakage to be semicircles, and that distances d_1'' and d_2'' between their nearest and furthest edges respectively are given ; also a'' their width along the parallel edge :—

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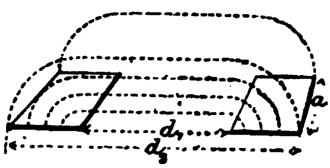
[1] *Journal Soc. Teleg. Engineers*, xv. 551, 1886.

$$\text{Permeance} = 2{\cdot}274 \times a'' \times \log_{10} \frac{d_2{}'}{d_1{}''}.$$

FIG. 110.



Rule III.—Permeance between two equal parallel rectangular areas lying in one plane at some distance apart. Assume (Figure 110) lines of leakage to be quadrants joined by straight lines.

$$\text{Permeance} = 2{\cdot}274 \times a'' \times \log_{10} \left\{ 1 + \frac{\pi (d_2'' - d_1'')}{d_1''} \right\}$$

Rule IV.—Permeance between two equal areas at right-angles to one another.

Permeance = double the respective values calculated by II.

If measures are given in centimetres these rules become the following :—

I. $\frac{1}{2}\,(A_1 + A_2) \div d.$

II. $\frac{a}{\pi}$ hyp. log $\frac{d_2}{d_1}$

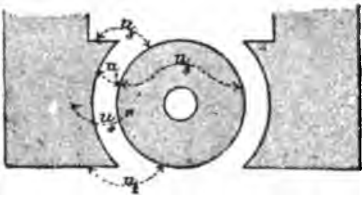
III. $\frac{a}{\pi}$ hyp. log $\left(1 + \frac{\pi (d_2 - d_1)}{d_1} \right)$

Using these rules Mr. Ravenshaw has developed them for the calculation of dynamos for Messrs. W. T. Goolden & Co. Applying them to predetermine the leakage to fly-wheels, pedestals, and shafts, he is thus able to predict the performance of a machine, from the working drawings, to within 2 per cent.

EXAMPLE OF LEAKAGE CALCULATIONS.

It is required to predetermine the coefficient of leakage of the Edison-Hopkinson dynamo described on p. 521 (Fig. 353), the dimensions of which are given on p. 413. This is the same machine the stray field of which is depicted in Fig. 106, p. 184.

FIG. 111.



We must first determine the items which go to make up the useful permeance u, then those which make up the waste permeance w; having found these calculate v. But since the permeance of the useful flux depends on the permeability of the iron core of the armature, it will be needful to calculate the value of u at several different stages of saturation.

Now the items of u are five in number, and must be evaluated separately.

u_1 *Permeance of one Gap-space* (by Rule I.).

$u_1 = 3 \cdot 1918 \ \frac{1}{2}$ (radius of core + radius of pole-piece) $\times \ 2 \pi \times \frac{\text{angle of pole face}}{360} \times$ length of pole-piece parallel to shaft ÷ distance from core to polar face,

$$= 3 \cdot 1918 \times (4 \cdot 812 + 5 \cdot 406) \times 3 \cdot 1416 \times \frac{129}{360} \times 19 \div \frac{19}{32};$$

whence

$u_1 = 1176.$

u_2 *Permeance into armature below poles* (Fig. 112).

Assume under surface is plane and apply Rule II.

$$u_2 = 2 \cdot 274 \times 19 \times \log \frac{5}{1};$$

$$= 2 \cdot 274 \times 19 \times 0 \cdot 703.$$

whence

$u_2 = 29.$

u_3 *Permeance into armature above, from limb* (Fig. 113).

FIG. 112.

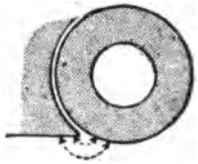


FIG. 113.

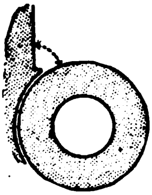


FIG. 114.

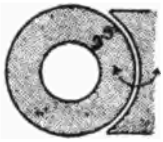
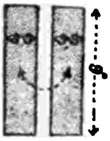


FIG. 115.



This is taken as twice u_2, since path of lines is half as long.
$u_3 = 58$.

u_4 *Permeance from flank of pole-piece to flank of armature core* (Fig. 114).

Apply Rule II. on assumption that these two areas (Fig. 114) act like two rectangles 9 inches long, 3·3 inches wide, and $\frac{1}{4}$ inch apart (Fig. 115).

$$u_4 = 2{\cdot}274 \times 9 \times \log \frac{3{\cdot}3}{0{\cdot}25}$$
$$= 2{\cdot}274 \times 9 \times 1{\cdot}206$$
$$u_4 = 24.$$

u_5 *Permeance of iron of armature through core.*

Assume average length of path from side to side to be $5\frac{1}{8}$ inches. It is needful to make three calculations, assuming three separate degrees of saturation of the core. Formula will be the reciprocal of that for the reluctance on p. 410.

[*a*] Core unsaturated: assume $\mu = 3000$

$$u_5 = 3{\cdot}1918 \times \frac{A\,\mu}{l};$$
$$= 3{\cdot}1918 \times 125 \times 3000 \div 5{\cdot}125;$$
$$u_5 = 233,550 \text{ (when unsaturated).}$$

[*b*] Core saturated up to $\mathbf{N} = 10,850,000$; or $\mathbf{B}_{,,} = 87000$:

whence by Table II., p. 146, $\mu = 900$. This corresponds to degree of excitation when machine is at full load (see p. 182).

$$u_5 = 3{\cdot}1918 \times 125 \times 900 \div 5{\cdot}125;$$
$$u_5 = 70065 \text{ (at full load).}$$

[*c*] Core saturated, as in more recent machines to $\mathbf{B}_{//} = 110{,}000$; whence by Table II., p. 146, $\mu = 160$.

$$u_5 = 3{\cdot}1918 \times 125 \times 160 \div 5{\cdot}125;$$
$$u_5 = 12456 \text{ (at high saturation).}$$

u Nett Useful Permeance.

Referring back to Fig. 111, we now see that the u_1, u_2, u_3, and u_4 are all in parallel with one another, and may be added; but that u_5 is in series with their sum, on each side; hence the nett permeance will be:—

$$u = \text{reciprocal of } \left\{ \frac{2}{u_1 + u_2 + u_3 + u_4} + \frac{1}{u_5} \right\};$$

and $u_1 + u_2 + u_3 + u_4 = 1287$.

Now take successively the three values found for u_5, and calculate u. This gives:—

[*a*]	(core unsaturated)	$u = 642{\cdot}2$
[*b*]	(core at full load)	$u = 638{\cdot}1$
[*c*]	(core saturated highly)	$u = 612{\cdot}4$

Next calculate the *waste field.*

w_1 *Permeance to bed-plate* (Fig. 106, p. 184).

This will be half the permeance under one pole-piece; and must be calculated by Rule I., assuming area of top of bed-plate.

$w_1 = \frac{1}{2} \times 3{\cdot}1918 \times \frac{1}{2}$ (area under pole + area of $\frac{1}{2}$ top of bed-plate $\div$ width of the gap between them.

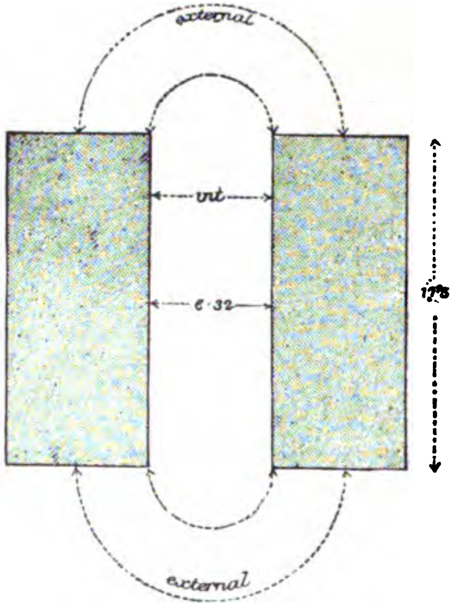
$= \frac{1}{2} \times 3{\cdot}1918 \times \frac{1}{2} (171 + 495) \div 5$

$w_1 = 106.$

w_2 *Permeance across limbs* (Fig. 116).

This consists of two parts, one external, one internal; they are calculated separately and added. *Internal part:* Calculate

FIG. 116.



by Rule I., but adding a breadth equal to radius of smallest arc, owing to spread of magnetic lines.

$$= 3 \cdot 1918 \times \tfrac{1}{2}\,(17\tfrac{1}{2} + 23\tfrac{13}{16}) \times 18 \div 6\,\tfrac{5}{16}$$
$$= 188.$$

External part: Calculate one of the flanks by Rule II., and double

$$= 2 \cdot 274 \times 18 \times \log\,(23 \cdot 8 \div 6 \cdot 22) \times 2$$
$$= 47 \cdot$$

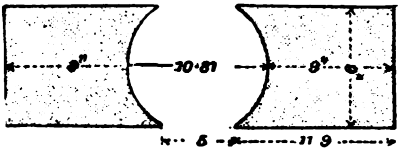
whence, adding the internal and external parts,

$$w_2 = 235.$$

w_3 *Permeance across flanks of pole-pieces.*

Treat these (as in Fig. 117) as blocks 9 inches high by 10 wide at a distance of 10·5 apart. Apply Rule II., and double.

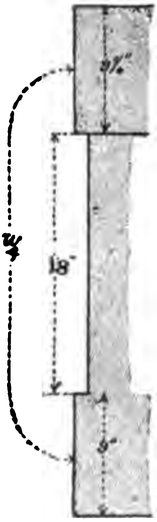
FIG. 117.



$$w_3 = 2{\cdot}274 \times 9 \times \log\,(30{\cdot}5 \div 10{\cdot}5) \times 2$$
$$w_3 = 19.$$

w_4 *Permeance from pole-pieces up to yoke* (Fig. 118).

FIG. 118.



Each pole-piece has three faces: imagine these spread out, to total breadth of 10 + 9 + 10 inches. Apply Rule III., and then take half because the two leakages are in series.

$$w_4 = 2{\cdot}274 \times 29 \times \log\left(1 + \frac{\pi \times 9}{18}\right) \div 2$$
$$= 14.$$

w *Nett permeance of stray field.*

Note that the leakages along the paths whose permeances are w_1, w_3, w_4, will be proportional to the difference of magnetic potential at the pole-pieces; but leakage along w_2 (between limbs), will be proportionately only half as great owing to fact that at upper end leakage is practically zero. Hence in adding up, take $\frac{1}{2}\,w_2$ instead of w_5 itself.

$$w = w_1 + \tfrac{1}{2}\,w_2 + w_3 + w_4$$
$$w = 256{\cdot}5.$$

v *Final calculation of leakage coefficient.*

There are again three cases corresponding to the three values of u, to be calculated by the formula:—

$$v = \frac{u + w}{u}$$

[i.] When iron is quite unsaturated.

$v = (641{\cdot}7 + 256{\cdot}5) \div 641{\cdot}7$

$v = 1{\cdot}399.$

[ii.] Core working to full load.

$v = (637{\cdot}6 + 256{\cdot}5) \div 637{\cdot}6$

$v = 1{\cdot}402.$

[iii.] Core highly saturated.

$v = (611{\cdot}9 + 256{\cdot}5) \div 611{\cdot}9$

$v = 1{\cdot}419.$

These results justify the opinion that the number assumed by the Hopkinsons (1·32) for this machine was too small.

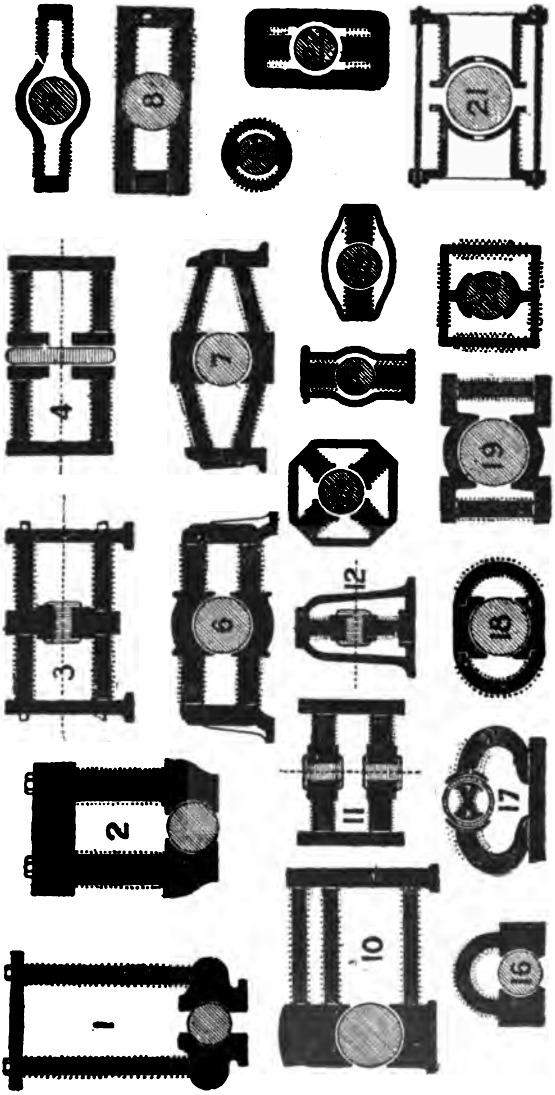
It may be noted in conclusion that the nett permeance of the waste field will, in a given type of machine, increase with both the length and diameter of the armature, being approximately proportional to the square root of the product of these two quantities. If two machines, built with the same size of core-disk, have armatures of different lengths, the machine with longer armature will have greater leakage permeance.

CHAPTER VIII.

FORMS OF FIELD-MAGNETS.

In Chapter III., on the elements of dynamos, something was said about the general principles which should be followed in the design of field-magnets. With the principle of the magnetic circuit to guide him, the reader will have little difficulty in judging of the relative value of the various designs; for he will remember that the magnetic circuit of highest permeability will have the most compact form, greatest cross-section, softest iron, and fewest joints. It has, moreover, been pointed out by Rowland that theoretically it is better that there should be one such magnetic circuit than that there should be two, though for practical structural reasons the author thinks the double circuit preferable in many cases. The double circuit, that is to say one resembling No. 3 or No. 8 of the accompanying Fig. 119, has in general the advantages that it affords a more stable framework, and that its magnetic field is generally more symmetrical than that of No. 2. These points should be borne in mind in considering the forms depicted in the accompanying figures. No. 1 of these illustrations shows the form adopted by Wilde for use with the shuttle-wound armature of Siemens. Two slabs of iron are connected at the top by a yoke, and are bolted below to two massive pole-pieces. There are four joints in the magnetic-circuit, in addition to the armature-gaps, and the yoke is insufficient. No. 2 shows the form adopted in the latest Edison dynamos (American pattern). The upright cores are stout cylinders. The yoke is of immense thickness; the pole-pieces are massive, but their lower corners are cut away. There are as many joints as in Wilde's form; but such a circuit would possess a far higher magnetic conductivity than Wilde's owing to the greater cross-section. One difficulty with such single circuit forms is how to mount

Fig. 119.



Typical Forms of Field-Magnets.

them upon a suitable bed-plate. If mounted on a bed-plate of iron, a considerable fraction of the magnetism will be short-circuited away from the armature, as has been shown in the preceding chapter. In the larger form, No. 10, used at one time by Edison, this difficulty was only partially obviated by turning the magnets on one side.

A favorite type of field-magnet, having a double magnetic circuit with consequent poles, is represented in No. 3; it was introduced by Gramme. It may be looked upon as the combination of two such forms as No. 1, with common pole-pieces. Nos. 3 to 9 may be looked upon as modifications of a single fundamental idea. No. 4 gives the form used in the Brush dynamo (plan), the two magnetic circuits being separated by the ring armature. The diagram will serve equally for many forms of flat-ring machine; but in most of these the poles at the two flanks of the ring are joined by a common hollow pole-piece, embracing a portion of the periphery of the ring. No. 5 shows an early form of Siemens, with arched ribs of wrought iron, having consequent poles at the arch. The circuit is here of insufficient cross-section. No. 6 depicts a form adopted by Weston: and very similar forms have been used by Crompton, and by Paterson and Cooper. There is a better cross-section here. No. 7 is a form used by Burgin and Crompton, and differs but slightly from the last. It has one advantage—that the number of joints in the circuit is reduced. No, 8 is a form used by Crompton, Kapp, and by Paterson and Cooper. No. 9 is the form adopted in the little Griscom motor. No. 18 is a further modification due to Kapp. No. 19, which also has consequent poles, is used by McTighe, by Joel, and by Hopkinson ("Manchester" dynamo), by Clark, Muirhead & Co. ("Westminster" dynamo), by C. E. Brown (Oerlikon), by Blakey, Emmett & Co., and in some of Sprague's motors; but with slight differences in proportions of the details. The main difference between No. 19 and No. 6, lies in the position selected for placing the coils, No. 19 requiring two, No. 6 four. No 20 which is a design of Elwell and Parker, is a further modification of No. 3, and would be improved by having a greater cross-section. In No. 3 (Gramme), it is usual to cast the pole-pieces and end-plates, but to use wrought iron for the longitudinal cores. The requisite polar surface must be got by some means, and when the core was made thin, the two courses open were either to fasten upon the core a massive pole-piece (Nos. 1, 3, 4, 6, 7, 19, 20), or else to arch the core No. 5 so that its lateral surface was available as a pole. Now, however, that it is known that massive cores are of advantage, the requisite polar surface can be obtained without adding any polar expansion or "piece," but by merely shaping the core to the requisite form (No. 8). This must not be regarded as a thinning of the magnet; for though mere reduction of cross-section at any part of the circuit would reduce the magnetic conductivity, reduction of the thickness for the purpose of bringing the armature more closely into the circuit will have quite the opposite effect. In fact the horizontal bars above and below the armature might be thinned away to nothing at their middle point, but for structural reasons. In all such forms of double magnetic circuit each half of the field-magnet may be regarded as having to furnish magnetic lines to its own half of the armature. Nos. 11 to 15 illustrate forms of field-magnet having *salient*, as distinguished from *consequent* poles. No. 11 is the double Gramme machine designed by Deprez. Nos. 12 and 13 are two of the innumerable patterns due to Gramme himself. These are both of cast iron; and it will be noticed that in No. 13 there are no joints, it being cast in one piece. No. 14 is the form used by Hochhausen, and is practically identical with 21, save in the position of the axis of rotation. The iron flanks of number 14 tend to produce a certain short-circuiting of the magnetism by their proximity to the poles; and their sectional area is insufficient. No. 15, used by Van de Poele, is similar. No. 16 is the form used by the author in small motors, and is cast in one piece. The semicircular form adopted for the core was intended to reduce the magnet circuit to a minimum length. No. 17 illustrates the form used by Jürgensen, having salient poles reinforced by other electromagnets within the armature. No. 21 shows in section the double tubular magnets of the

Thomson-Houston dynamo, the spherical armature being placed, as in Nos. 12, 14, and 15, between two salient poles.

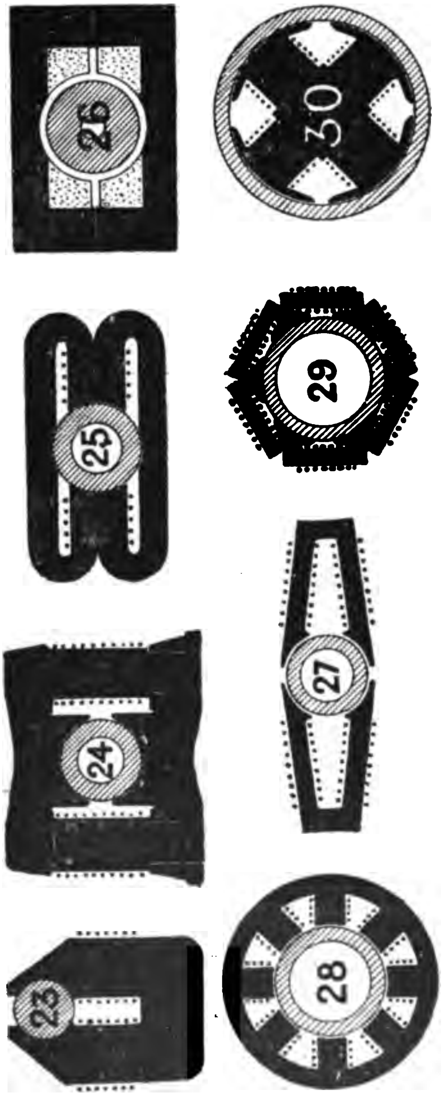


FIG. 120.

TYPICAL FORMS OF FIELD-MAGNETS.

There is a curious analogy between Nos. 21 and 19; but they entirely differ in the position of the coils. No. 22 is a design by Kapp, in which there are two salient poles of similar polarity, and two consequent poles between them, one pair of coils sufficing to magnetize the whole quadruple circuit. Almost identical forms have been employed by Kennedy (" iron-clad " dynamo). Lahmeyer and Wenström employ iron-clad forms resembling No. 15. That of Wenström has for its yoke an external iron cylinder. No. 23, Fig. 120, is a type which, used long ago by Sawyer and by Lontin, has recently become a favourite one, having been revived almost simultaneously by Gramme (" type supérieur "), by Kapp, by Siemens (" F " type), by Cabella (" Technomasio "), and by Paterson and Cooper. No. 24 is Brown's very massive form. No. 25 is Kennedy's " iron-clad " dynamo : the iron cores are forged to shape. No. 26 is designed by Professor

Fig. 121.

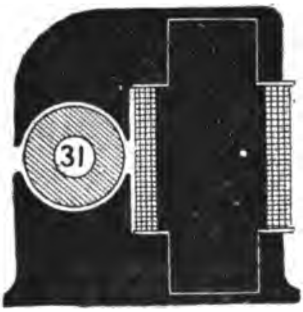


Fig. 123.

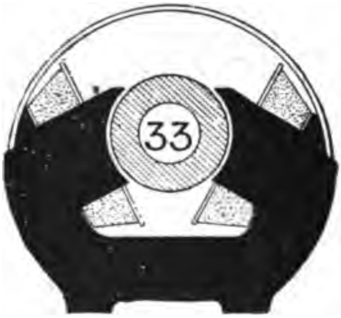
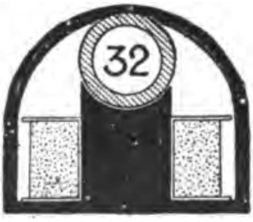


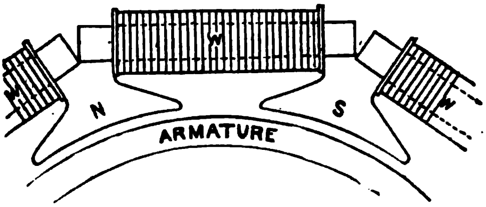
Fig. 122.



Typical Forms of Field-Magnets.

George Forbes. The ironwork is in two halves; the coils, which are entirely enclosed, are so placed as to magnetize the armature directly, one coil occupying all the available space between the field-magnet and the upper half of the armature; the other the similar space around the lower half. Eickemeyer, of Yonkers, uses a closely kindred form. No. 27 is the four-pole form adopted by Elwell and Parker in some of their larger machines. No. 28 is a multipolar form used by Wilde, Gramme, and others, the poles which surround the ring being alternately of opposite sign. It is now largely used for alternate-current machines such as those of Westinghouse (Stanley), Mather and Platt (Hopkinson), Paterson and Cooper (Esson), Elihu Thomson, Blakey and Emmott, and others. In No. 29, a modification of this design by Thury, for use with a drum armature, the six inwardly-directed poles are magnetized by coils wound upon the external hexagonal frame. This construction is shown in detail in Fig. 125. The cores which receive the windings are slabs of wrought iron, and are bolted to intermediate pole-pieces of cast iron. No. 30 is a sketch of a recent form adopted by Siemens and Halske, wherein an external ring rotates outside a very compact and substantial four-pole electromagnet. Similar machines have been designed by Ganz, Fein, and others, and are largely used in Germany for large central-station machines.

FIG. 125.

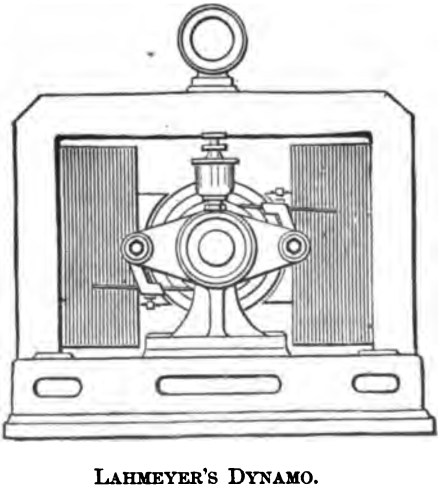


DETAIL OF THURY'S FIELD-MAGNET.

Another recent form of field-magnet is shown in No. 31. This, which is a single horse-shoe with but one coil upon it, was a design by the author of this work early in 1886: and a similar form was independently designed by Goolden and Trotter about the same time. One-coil machines have also been recently designed by Schorch, of Darmstadt, and by R. Kennedy, of Glasgow, by Immisch, and by J. G. Statter and Co. No. 32 represents also a machine requiring but one coil and is of the iron-clad type. It was devised by McTighe in 1882, and has been recently revived by Stafford and Eaves. A recent pattern designed by Mordey for the Brush Company resembles No. 32, but has an external iron cylinder to enclose the coil. No. 33 represents the latest machine of Fein, of Stuttgardt, with inward-pointing poles.

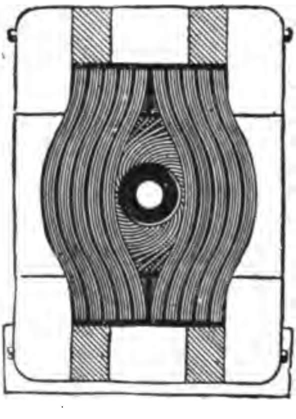
In Fig. 126 is represented Lahmeyer's form, also with inward-pointing poles. (See also Fig. 107, p. 185.)

FIG. 126.



LAHMEYER'S DYNAMO.

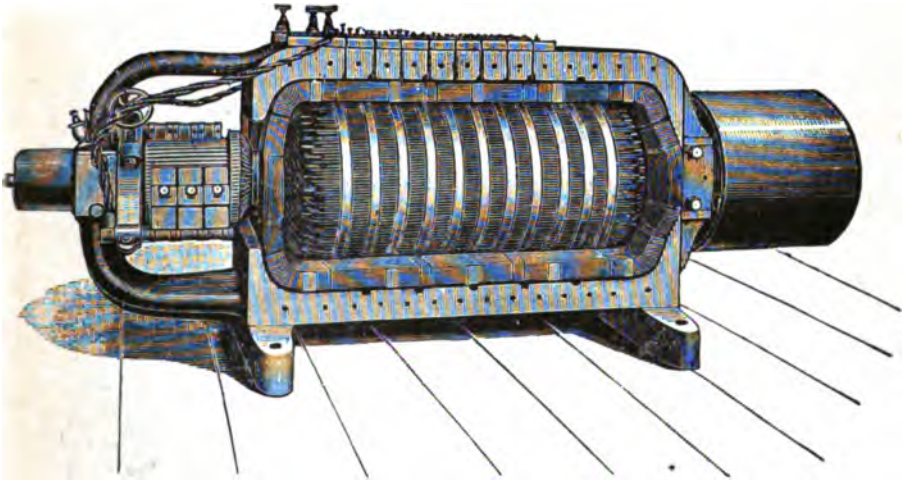
FIG. 127.



EICKEMEYER'S DYNAMO.
(showing coils).

Eickemeyer's dynamo (Fig. 127) realizes the suggestion of Forbes to place the magnetizing coils over the armature. The coils, which are separately wound on formers, fit into recesses between the upper and lower yokes and the inwardly projecting polar masses. Fig. 128 gives a view showing the interior disposition when one of the polar masses is removed. The defect of such forms is the difficulty of ventilating the closely enclosed armature.

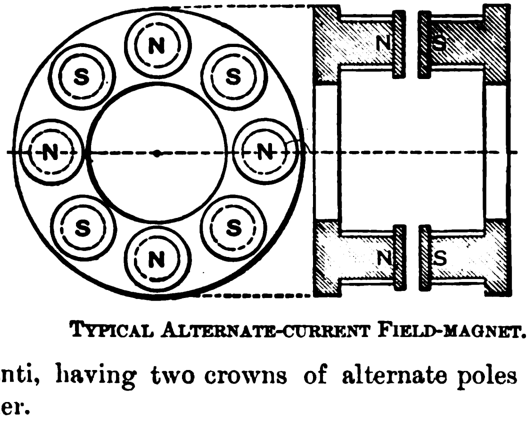
FIG. 128.



EICKEMEYER'S DYNAMO, WITH MAGNETIZING COILS SURROUNDING ARMATURE.

A typical form for alternate-current machines is that introduced by Wilde and used by Siemens, Gordon and Ferranti, having two crowns of alternate poles facing one another.

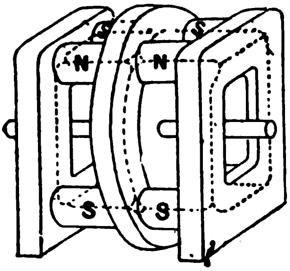
FIG. 129.



TYPICAL ALTERNATE-CURRENT FIELD-MAGNET.

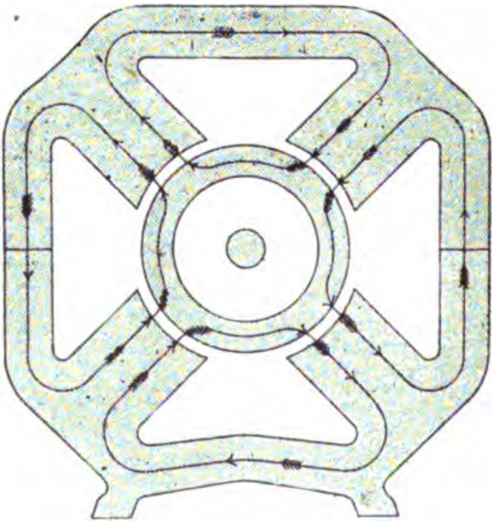
Fig. 130 represents a form of four-pole field-magnet used by the Brush Company for their Victoria (Mordey) machines, having double magnetic circuits and consequent poles. The cores to receive the coils are of wrought iron, whilst the end frames and pole-pieces are cast. This should be contrasted with the form of four-pole magnet used by Brown, of Oerlikon, in some large 300 horse-power machines for transmission of power. These are made entirely of cast iron, and have salient poles. The direction of the flux through these machines is indicated by dotted lines.

Fig. 130.



Four-pole Magnet (Mordey).

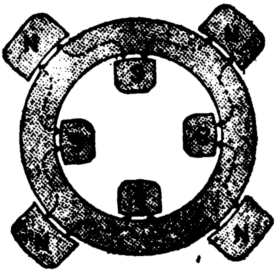
Fig. 131.



Four-pole Magnet (Brown).

The most notable departure in the forms of field magnets in recent years is that due to Mordey, in whose alternator there is a field-magnet (see Plate XXI. Fig. 1), which though it possesses but a single magnetic circuit with one exciting coil upon it, is nevertheless multipolar. This result is attained by the use of multiple pole-pieces which subdivided the magnet flux into a number of separate magnetic fields. Another recent example of a multipolar machine (eight-pole) having a single magnetic circuit is afforded by the Edison Company's "marine" dynamo,[1] with a ring armature acted on by four internal and four external poles. The exciting coil lies behind the armature between the two sets of poles. The field-magnet of the three-phase alternator (Plate XXVIII.), designed by Brown for the transmission of power from Lauffen to Frankfort, is also of this improved kind, with a single exciting coil.

FIG. 132.



EDISON CO.'S MARINE DYNAMO.

Among such a multiplicity of designs one seeks for some indication as to the best. But the best for one purpose is not the best for all. Some designs are suitable for cast iron; others for wrought iron; others again, such as Figs. 121 and 130 are expressly intended to be composite, having wrought cores for the bobbins and cast polar masses. For small machines a simple circuit is probably the best. For large machines it is found needful to multiply the number of poles: and for alternators, multipolar forms are necessary for obtaining a sufficiently frequent alternation of currents.

Probably the future will see a general simplification of multipolar forms by the adoption of branched magnetic circuits.

In calculating those forms which have double or multiple magnetic circuits it is usual to simplify matters by considering one element of the whole, and making the calculations for it. Thus, for example, in Fig. 133, which depicts the half of such a machine as No. 8 of Fig. 119, it is sufficient to calculate the magnetic reluctances of half the machine in order to ascertain the number of ampere-turns that must be wound upon it; a similar number being wound upon the other half. Forms with a double-magnetic circuit are preferable to those, such as Nos. 2, 23, and 31, with a single magnetic circuit, in all cases where there is likely to be much armature reaction. For in such forms as No. 23 the field is weaker under the two upper pole-tips than between the two lower ends of the pole-faces: in consequence, there is a powerful attraction downward of the armature. Further, because of this inequality of field the cross-magnetizing force of the armature will produce, in the single-magnet forms, an unsymmetrical distortion. As a consequence there is sure to be sparking at the brushes. For large-load armatures it is advisable not only to use double magnets, but to separate their two halves by a distance-piece of brass.

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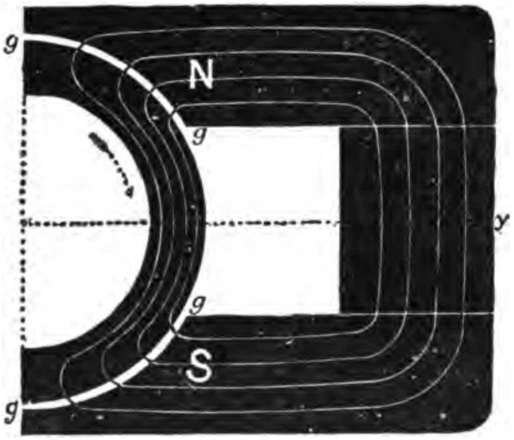
[1] *Electrical World*, xiii. 201, 1889; for a similar design by Mariotti, see *Electrician*, xxv. 189, 1890.

FIG. 133.



HALF OF A DOUBLE MAGNETIC CIRCUIT MACHINE.

CHAPTER IX.

ELEMENTARY THEORY OF THE DYNAMO. MAGNETO, AND SEPARATELY-EXCITED MACHINES. SERIES MACHINES. SHUNT MACHINES.

Experience has shown that the main problems that require to be considered in the design of dynamos, are best solved by reference to the *magnetic circuit of the machine as a whole*, the iron core inside the armature being regarded as a constituent part of that circuit, and not as something which merely increases the effective area of the armature coils. In all that follows the armature is regarded merely as consisting of a certain number C of conductors, grouped in a particular way around an axis of rotation, their function being to cut across a certain actual number of magnetic lines that are furnished by the magnetic circuit. Also the symbol **N** stands, in the case of 2-pole machines, for *the whole number of lines of magnetic force that traverse the armature*, entering it on one side and again leaving it on the other; it is called by some writers the "total induction" through the armature, by others the "magnetic flux." For multipolar machines, **N** refers to any *one* of the separate magnetic circuits.

The number of revolutions *per second* made by the armature is denoted by the symbol n. It is found that the average electromotive-force generated by the armature is simply proportional to each of these quantities, so that by taking the appropriate units we may write, as will presently be seen, as the fundamental equation

$$\text{(average) } E = n\,C\,\mathbf{N} \quad . \quad . \quad . \quad . \quad \text{[I.]}$$

In the earlier editions the field-magnet was regarded apart from the armature or its core, as having the function of creating a magnetic field; and the armature was regarded simply as a complex coil having a certain "effective area," rotating in that field. The average intensity of the field was denoted by the symbol H, and the equivalent effective area by A: the electromotive-force of the dynamo being proportional to the product of the two, and the speed n; or as it was written

$$\text{(average) } E = 4 n A H.$$

There was nothing incorrect in this way of regarding the matter; but neither A nor H were quantities that could be easily determined during the different stages of action of the machine. The iron core of the armature, in the present mode of treating the subject, is now regarded as having nothing to do with C, the armature factor, but as playing its part in the magnetic circuit in determining how many magnetic lines, namely **N**, shall be cut by the armature in its rotation. In brief, instead of trying to find an average *intensity*, we endeavour to think of the magnetic field as a whole—we endeavour to think of the *quantity* of it.

In the present chapter an expression is first found for the average electromotive-force, which expression serves as the fundamental equation of all dynamos. Then by introducing appropriate formulæ for the various circuits, equations are deduced for the various kinds of series-wound, shunt-wound, and compound-wound dynamos.

SYMBOLS USED.

It may be well to point out that in this and the succeeding chapters the following symbols are used in the following significations:—

A	area, expressed in *square centimetres.*
B	the magnetic induction, or number of magnetic lines per square centimetre.
b	number of external wires in a section of the armature.
β	angular breadth of a section of armature coil or of segment of collector.
C	number of conductors on the armature, counted all round the external periphery.
c	number of segments of collector or commutator.

E	entire electromotive-force generated in an armature,	expressed in *volts.*
ϵ	difference of potential from brush to brush,	
e	difference of potential from terminal to terminal,	
E	electromotive-force of some external supply of electricity,	
η	economic coefficient, or efficiency (see pp. 234 and Chap. XXVIII.).	
F	force (i. e. push or pull), expressed in either *dynes*, *poundals*, *grammes'* weight, or *pounds'* weight.	
H	Intensity of magnetic field (lines per sq. centim. *in air*).	
i	current in external circuit,	expressed in *amperes.*
i_a	current in armature,	
i_s	current in shunt coil,	
i_m	current in series coil of field-magnet,	
L	coefficient of self-induction.	
λ	average length of one turn of wire; also used for angle of lead.	
μ	coefficient of magnetic permeability of iron.	
N	whole number of magnetic lines that traverse a magnetic circuit.	
n	number of revolutions *per second.*	
ω	angular velocity (expressed in *radians*-per-second).	
p	number of *pairs* of poles.	
R	resistance of external circuit,	expressed in *ohms.*
r_a	resistance of armature coils,	
r_s	resistance of shunt coils,	
r_m	resistance of series coil on field-magnets,	
r	internal resistance of dynamo; equal to $r_a + r_m$ or to $r_a + r_s$ according to circumstances,	
ρ	resistance per unit of length,	
S	number of turns of wire in field-magnet coil in series with armature. Also, in general, for number of spirals.	
T	torque, or turning-moment, or angular force, or couple, or "effort statique," or "statisches Moment," expressed in *dyne-centimetres*, *gramme-centimetres*, *metre-kilogrammes*, or *pound-feet*, according to circumstances.	
T	is also used in the section on alternate-current dynamos for the periodic time of the alternating current, measured in *seconds.*	
t	time, measured in *seconds.*	
ν	coefficient of allowance for magnetic leakage.	
W w	activity, or power, or work-per-second, expressed in *watts* or in *horse-power.*	
Z	number of turns of wire in shunt field-magnet coil.	

Wherever inch units are used instead of centimetre units, the marks already used on p. 142 will be employed for distinction.

FUNDAMENTAL EQUATION OF DYNAMO.

To find the average electromotive-force of a moving conductor, we must remember that, by definition, see page 20, this is (in absolute C.G.S. units) numerically equal to the number of magnetic lines that are cut in one second by the conductor. Also the practical unit, the *volt* being (see Appendix A) by definition equal to 10^8 absolute C.G.S. units of electromotive-force; it will be necessary to divide the number of C.G.S. units by 10^8 in order to reduce the number to volts. Further, when there are, as in the armatures of dynamos, a number of conductors in series with one another, the total electromotive-force of the dynamo will be equal to the sum of the electromotive-forces of those conductors that are in series with one another. The fundamental equation will then be written:—

$$\text{(average) E (in } \textit{volts}\text{)} = n\,\mathrm{C}\,\mathbf{N} \div 10^8 \quad . \; . \; . \; . \; . \quad [\mathrm{I}a.]$$

We will deal first with an ordinary two-pole dynamo, having an armature in which the number of "sections" is denominated by the symbol *c*; the number of "segments" or "bars" in the commutator or collector will also be *c*. Let there be in each section *b* external wires or conductors, as counted on the outside of the armature core. (In ring-armatures there will be the same number of external wires as there are loops or windings in the section; in drum armatures there are twice as many external wires as there are loops or windings in the section.) Then the number of external conductors or wires, reckoned all round the armature will be $b\,c$; it will be more convenient to use the single symbol C for this number. The number of external conductors or wires that are in series with one another electrically from brush to brush will be $\frac{b\,c}{2}$ or $\frac{1}{2}$ C. Now let the armature rotate with a speed of n revolutions per second. (Engineers usually count the revolutions made in one minute, necessitating division by 60 to get n.) Then one revolution will take $\frac{1}{n}$ part of 1 second.

We are now ready to calculate the electromotive force.

No. of lines cut by 1 *external wire in* 1 *revolution* .. .. $= 2\,\mathbf{N}$;

(because each wire cuts all the lines where they go in at one side of the armature, and where they come out on the other).

No. of lines cut by 1 *external wire in* 1 *second* $= 2\,n\,\mathbf{N}$;

No. of lines cut by $\frac{1}{2}$ C *external wires in series in* 1 *second* .. .. $= 2n \times \mathbf{N}\,\frac{1}{2}\,C$;

No. of lines cut by $\frac{1}{2}$ C *external wires in series in* 1 *second* .. .. $= n\,C\,\mathbf{N}$.

Average electromotive-force (in C.G.S. units) $= n\,C\,\mathbf{N}$;

Average electromotive force (in *volts*) .. .. $= \dfrac{n\,C\,\mathbf{N}}{10^8}$ . . [I*a*.]

It will be unnecessary in every case to write the divisor 10^8 in the formula, because it is easily remembered that, if omitted for the sake of brevity, the numbers obtained can be transformed at once to volts[1] by so dividing down.

For many purposes it is more convenient to have the fundamental equation in terms of the angular velocity. Let the symbol ω represent the angular velocity. Then

$$\omega = 2\,\pi\,n$$

for, in each revolution, the angle described is $2\,\pi$ *radians* or 360 *degrees*. Consequently $n = \dfrac{\omega}{2\,\pi}$, which gives;

$$(\text{Average})\ E = \frac{\omega}{2\,\pi}\,C\,\mathbf{N} \quad . \ . \ . \ . \ . \ . \quad [\text{I}b.]$$

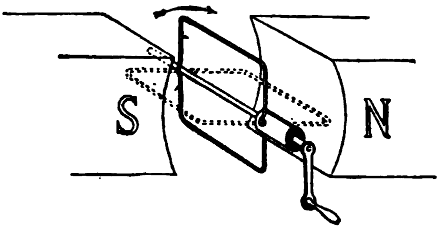
It will be observed that this electromotive-force is simply an average; and it depends on the construction of the armature how much fluctuation there is in the value during a rotation.

---

[1] Another way of lightening the formula would be to adopt as the unit quantity of magnetic flux, one hundred million lines, and in that case the symbol **N** would be used for the number of bundles of lines containing a hundred million each. But very few dynamos have been constructed in which the magnetic flux attained so great a quantity as one such bundle. The awkwardness of having the values of **N** always fractional would scarcely be compensated for in the gain of having a unit which fits so conveniently to the other practical international units. No difficulty is likely to arise from the omission of the divisor in the formulæ.

If, as in Fig. 134, the armature had but two external conductors forming a simple loop, then the electromotive-force would fluctuate between zero and a maximum. Calling the lowest point of the rotating loop in its vertical position 0°, then the position on the left of the dotted line will be 90°, if we reckon the angle of rotation in the clockwise direction. The top point will be 180°, and the point on the extreme right 270°. Then the induced electromotive-force will be zero as the coil passes through 0° and 180°, for at the positions 0° and 180° the conductors will be sliding along, rather than cutting, the magnetic lines, and a maximum as the coil passes through 90° and 270°. The *rate* of enclosing or " cutting " will be a *maximum* when the *actual number* of lines enclosed is a *minimum*, and *vice versâ*. (See p. 32.)

FIG. 134.



IDEAL SIMPLE DYNAMO.

At any intermediate angle, if the field is uniform, the actual number of lines of force enclosed is proportional to the cosine of the angle through which the coil has turned from its zero position, and the electromotive-force will be proportional to the sine of that angle. Strictly speaking, we ought to take the sine with a *negative* value to represent the electromotive-force, because as usually defined the induced electromotive-force is proportional to the rate of *decrease* in the number of lines of force enclosed. We need not, however, trouble about signs, because, if the commutator is properly set, all the induced electromotive-forces are thereby made to act in the same direction through the external circuit. The exact expression at any particular angle θ, for the electromotive-force of the loop may be calculated as follows:—The number of lines of force enclosed when the loop has turned through angle θ is $= \mathbf{N} \cos \theta$; hence the rate of cutting will be $\omega \, \mathbf{N} \sin \theta$, or $2 \pi n \mathbf{N} \sin \theta$. Now, since the average value of $\sin \theta$, between the limits $\theta = 0°$ and $\theta = 90°$, is $\frac{2}{n}$, the *average* electromotive-force *per loop* may be obtained by substituting this value, giving us $\frac{2}{\pi}$

$$\text{Average E per loop} = 4 \, n \, \mathbf{N}.$$

And since the number of loops that are in series between brush and brush is $\frac{1}{4}$ C, we have finally

$$(\text{Average}) \; E = n \, C \, \mathbf{N}.$$

If the coil consisted of many turns all wound in one group, like the Siemens shuttle-wound armature, p. 33, the same expressions would obviously hold good on substituting the proper number for C.

Fluctuations of Electromotive-force in a One-coil Armature.

As explained above, the actual induced electromotive-force is proportional to the sine of the angle through which the coil has turned, or

$$E = 2 \pi n \mathbf{N} \sin \theta \times \tfrac{1}{4} C,$$

whence

$$E = \frac{\pi}{2} n \, C \, \mathbf{N} \sin \theta \quad . \; . \; . \; . \; . \; . \; . \quad [\text{II.}]$$

As θ increases from 0° to 360°, the value of the sine goes from 0 to 1, then from 1 to 0, from 0 to -1 and from -1 back to 0. The values of the sine are depicted in Fig. 135. The same curve may serve then to show how the electromotive-force would fluctuate if there were no commutator. But the action of the commutator is to commute the negative inductions into positive ones; the brushes being so arranged as to slide from one part of the commutator to the other at the moment when the inverse induction begins. This gives the curve the form of Fig. 136, which therefore represents how the voltage pulsates in the circuit of a simple old-fashioned shuttle-wound Siemens armature. Now if we could level these hills, and change our undulating induction into a steady one, we should get a single straight line, shown in Fig. 136 as a dotted line enclosing below it a rectangular area equal to the sum of the areas enclosed by the sinuous curves, and therefore at a height which is the average of the heights of all the points along the curves: in fact, since each sinuous curve is part of a curve of sines, the *average* height will be $\frac{2}{\pi}$, or about $\frac{7}{11}$ of the maximum height. In consequence of self-induction in the coils, the current will not actually fluctuate[1] as much as the voltage, the hollows being partly filled.

FIG. 135.

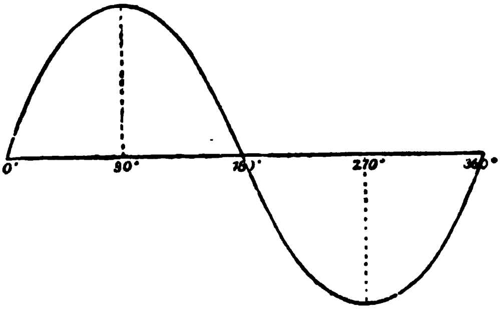
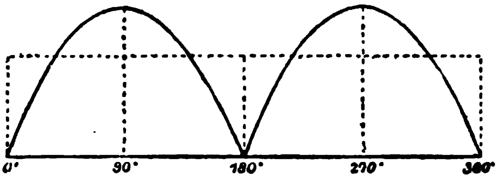


FIG. 136.



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[1] See remarks by Cromwell F. Varley in *Phil. Mag.*, 1867, and by Puluj in *Sitzungsber. Wien. Akad.*, II.*a*, May, 1891.

Fluctuations in a Closed-coil Armature divided into Sections.

As shown in the argument on pp. 40 and 41, it is, for reasons of construction, usual to wind armature coils in two sets connected in parallel. The two halves of the Pacinotti ring or the two halves of the windings on the Siemens drum meet at the brushes in parallel. If each of the two coils consisted of 100 turns, their joint effect in inducing electromotive-force would be no greater than that of either of them separately, but the internal resistance of the armature would be halved. From this point onwards in the argument it will be assumed that the armature windings consist of *pairs* of coils. Thus, instead of one coil of 200 turns, as shown in Fig. 137, we shall take it that there is a pair of coils each of 100 turns, as in Fig. 138.

Fig. 137.

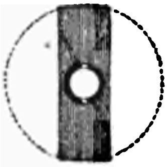


Fig. 138.

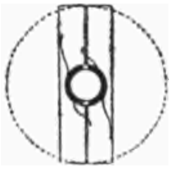
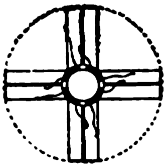
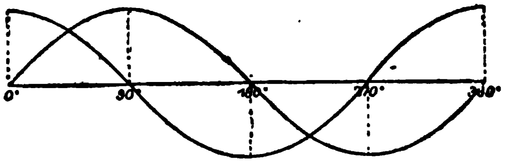


Fig. 139.



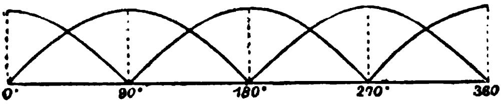
Now suppose that, in order to get a less fluctuating effect, we divide each of our original single pair of coils into two parts, and set these at right angles to one another. To take a numerical case, suppose there were originally 100 turns in each coil, and we split each into two coils of fifty turns, but set them across one another so that one comes into the best position in the field as the other is going out of it. (This arrangement is indicated in Fig. 139, which may be contrasted with Fig. 138 representing the undivided coil.) In this case we shall have two sets of overlapping curves—each of them will have to be but half as high as before, because the equivalent area of each coil is only half what it was for the whole coil. Then, if there were no commutator, the induced electromotive-force in the two sets of coils would fluctuate as shown by the two curves of Fig. 140. But if the ends of the two "sections" of the coil are joined to a proper commutator or collector, all the "inverse" inductions will be commuted into "direct" ones by the sliding of the brushes at the right moment, and the two curves would then become

FIG. 140.



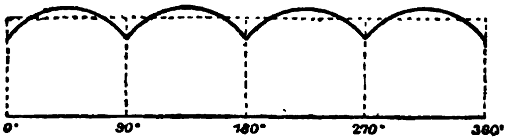
as in Fig. 141. The next process is to ascertain what the joint result of these over-lapping electromotive-forces will be: it is evident that from 0° and 90° the two inductive actions are assisting one another, and that at 45° they are equal. The nett result here is therefore double either of them; and,

FIG. 141.



in fact, the curve representing the *sum* of the two curves is given in Fig. 142. This curve shows at once a step towards *continuity*, as the fluctuations are far less than those of the single coil, Fig. 136. If, as before, we level the undulating

FIG. 142.



tops by a dotted line, we get precisely the same height as before. The *total* amount of induction (the total number of lines of force cut) is the same, and the *average* electromotive-force is the same. There is no gain, then, in the total electric work resulting from rearranging the armature coils in two sets at right angles to each other; but there is a real gain in the greater continuity and smoothness of the current.

If we again split our coils and arrange them as shown in Fig. 143 at angles of 45°, in four sets of pairs of coils of twenty-five turns each, and connect them up to a proper commutator, we shall get an effect which is very easily represented by constructing two curves, each similar to the last but each of half the height, and compounding them together (Fig. 144). One of them will of course have the maximum heights of crests occurring 45° further along than those of the other curve; and when these are compounded together we get for a resultant a curve shown in Fig. 145, which has exactly the same *average* height as before, but which has still less of fluctuation. It is easily conceived that this process of dividing the coil into sections, and spacing these sections out at equal angles symmetrically, would give us a result approaching as near as we choose to an absolutely continuous one. If our original pair of coils of 100 turns each were split into twenty sets of pairs of five turns each, or even into ten sets of pairs of ten turns each, the approach to continuity would be very nearly truly attained. It only remains to calculate the continuity algebraically; which, though not difficult, is rather tedious.

Fig. 143.

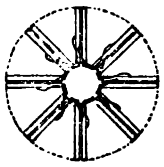


Fig. 144.

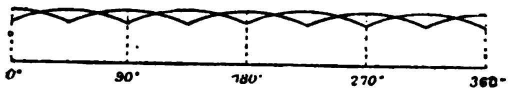
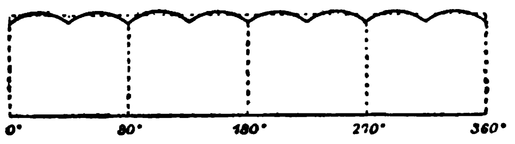


Fig. 145.



Calculation of Fluctuations of the Electromotive-force in Closed-coil Armatures.

We have seen in Chapter III. that in every armature a section of the coil connected with any two commutator-bars is undergoing at every instant an inductive effort exactly similar, but opposite in sign, to that going on in the section connected with the two bars on the side of the commutator diametrically opposite. We likened the two sets of coils in the two halves of the armature to two sets of galvanic cells arranged in parallel. Suppose the armature had in all thirty-six sections, then in reality there are two sets of eighteen, and the electromotive-force induced in each set is alike. We will take the case of a ring armature as being less complicated than the drum. Let the symbol c stand for the total number of sections in the armature. There will be therefore $\frac{c}{2}$ sections in each half of the armature from brush to brush. Let each section consist of b turns of wire. The whole armature will consist of $b\,c$ turns. If these c sections are set symmetrically round, the angle between the plane of each section and the next one to it will be $\frac{360}{c}$ degrees or $\frac{2\,\pi}{c}$ radians. This may for some purposes be written $\frac{\pi}{\frac{1}{2}\,c}$; and for shortness we will call this angle $= \beta$. We will then calculate the total electromotive-force induced in one set of sections, that is to say, in one of the rows $\frac{1}{2}\,c$ sections of coils extending half round the armature and commutator from one brush to the other. Referring to and remembering that only $\frac{1}{2}$ **N** lines, at most, go through any one section at any instant, we see that in the first section, when it has turned through angle θ, the induced electromotive-force e_1, will be

$$e_1 = \omega\,\frac{\mathbf{N}}{2}\,b\sin\theta,$$

where ω is the angular velocity. In the second section the electromotive-force will be

$$e_2 = \omega\,\frac{\mathbf{N}}{2}\,b\sin\,(\theta + \beta),$$

because this section has a position differing by an angle β from the first section. In the third section we have similarly

$$e_3 = \frac{\mathbf{N}}{2}\,b\sin\,(\theta + 2\,\beta)\,;$$

and so on, until we come to the last section of the set, for which the electromotive-force will be

$$e_{\frac{1}{2}c} = \omega \frac{\mathbf{N}}{2} b \sin \left(\theta + \overline{\tfrac{1}{2}c - 1}\, \beta\right).$$

But the whole electromotive-force of the set is the sum of all these separate electromotive-forces; so we have

$$\mathrm{E} = \omega \frac{\mathbf{N}}{2} b \times$$

$$\left\{ \sin \theta + \sin (\theta + \beta) + \sin (\theta + 2\beta) \ldots\ldots \sin \left(\theta + \overline{\tfrac{1}{2}c - 1\beta}\right) \right\}.$$

We can get, however, no information with respect to the maximum and minimum values of this fluctuating electromotive-force as long as the expression for E is in the form of a long series of values. We must proceed to sum this series within the brackets.

Inserting this value, we get at once

$$\mathrm{E} = \omega \frac{\mathbf{N}}{2} b \frac{\cos\left(\frac{\beta}{2} - \theta\right)}{\sin \frac{\beta}{2}}.$$

The amount of fluctuation implied in this formula depends on how the brushes are set. They slide, of course, from one bar of the commutator to another while the commutator moves through the angle β. So if $\theta = 0$ at the beginning, when the commutator-bar is just beginning to touch the brush, then $\theta = \beta$ just as the bar leaves contact with the brush. And when the brush touches the middle of the bar $\theta = \frac{\beta}{2}$. Now the cosine is a maximum when the angle is a minimum. Therefore E will be a maximum when $\frac{\beta}{2} = \theta$, *i. e.* when $\frac{\beta}{2} - \theta = 0$: and E will be a minimum when either $\theta = 0$, or $\theta = \beta$. We have, consequently, the following results as the bar of the commutator passes under the brush:

(1) At beginning ($\theta = 0$),

$$\mathrm{E}\ (\text{a minimum}) \ldots \ldots = \omega \frac{\mathbf{N}}{2} b \frac{\cos \frac{\beta}{2}}{\sin \frac{\beta}{2}}$$

$$= \omega \frac{\mathbf{N}}{2} b \operatorname{cotan} \frac{90^\circ}{\frac{1}{2}c}.$$

(2) At middle of bar $\left(\theta=\frac{\beta}{2}\right)$,

$$\text{E (a maximum)} \quad . \quad . \quad . \quad = \omega \frac{\text{N}}{2} b \frac{1}{\sin\frac{\beta}{2}}$$

$$= \omega \frac{\text{N}}{2} b \operatorname{cosec} \frac{90^\circ}{\frac{1}{2}c}.$$

(3) At end $(\theta=\beta)$,

$$\text{E (again a minimum)} \quad . \quad . \quad = \omega \frac{\text{N}}{2} b \frac{\cos\frac{\beta}{2}}{\sin\frac{\beta}{2}}$$

$$= \omega \frac{\text{N}}{2} b \operatorname{cotan} \frac{90^\circ}{\frac{1}{2}c}.$$

The greatest fluctuation therefore that can occur, will be the difference between cosec $\frac{90^\circ}{\frac{1}{2}c}$ and cotan $\frac{90^\circ}{\frac{1}{2}c}$; and, since each bar as it passes under the brushes comes into the position just occupied by the bar preceding it, there will be as many fluctuations in every revolution as there are bars in the commutator or sections in the armature, namely c. Further than this, if we could increase the number of sections indefinitely, so that $\frac{90^\circ}{\frac{1}{2}c}$ or $\frac{\beta}{2}$ was practically $=0^\circ$, then both cosec $\frac{90^\circ}{\frac{1}{2}c}$ and cotan $\frac{90^\circ}{\frac{1}{2}c}$ would be equal, and would be equal to $\frac{c}{\pi}$; for $\frac{90^\circ}{\frac{1}{2}c}=\frac{\pi}{c}$, and for small angles the arc is sensibly equal to either the sine or the tangent. We will, however, calculate the actual amount of fluctuation in certain cases. Many dynamos are built with armatures having a 36-part collector, and thirty-six sections in the armature coil. We want to know the fluctuations in this case, and in other cases with fewer or more segments. The following table gives the results of the calculations; the number of sections of the armature and commutator being given in the first column, and their angular breadth in the second. The fluctuation is the difference between columns 3 and 4:—

c	β	$\dfrac{\operatorname{cosec}\frac{\beta}{2}}{c}$	$\dfrac{\operatorname{cotan}\frac{\beta}{2}}{c}$	The Fluctuation.	Percentage Fluctuation.
2	180°	·5	0·	·5	±50·00
4	90	·3479	·2500	·0979	14·04
10	36	·3236	·3077	·0159	2·38
12	30	·3220	·3110	·0110	1·70
15	24	·3206	·3136	·0070	1·10
20	18	·3196	·3157	·0039	·61
24	15	·3192	·3165	·0027	·42
30	12	·3189	·3171	·0018	·28
36	10	·3187	·3175	·0012	·19
40	9	·3186	·3177	·0009	·14
45	8	·31857	·31780	·00077	·12
60	6	·31846	·31802	·00044	.07
90	4	·31838	·31819	·00019	·03
360	1	·31832	·31830	·00002	·003
5400	0° 4′	·3183099	·3183098	·0000001	·00001

From these figures it is apparent that the fluctuations become practically insignificant when the number of sections is increased; as indeed the curves of Figs. 136 to 145 showed. With a 20-part commutator the fluctuations of the electromotive-force in the armature are less than 1 per cent. of the whole electromotive-force. With a 36-part commutator, they are less than one-fifth of 1 per cent. So far as mere fluctuations are concerned then, it is practically a useless refinement to employ commutators of more than thirty-six parts. But there are other reasons, as we shall see in considering the self-induction in the separate sections, for making the number of sections as great as possible.

Now, assuming that we wind our coil in a large number of sections, so that the fluctuations may be negligible, what will the total electromotive-force be? We may write, as we have seen, $\frac{c}{\pi}$ for either cosec $\frac{\beta}{2}$ or for cotan $\frac{\beta}{2}$, giving us $E = \omega \frac{N}{2} b \frac{c}{\pi}$. Now $\omega = \pi n$, and $b\,c = C$, so that our formula once more becomes $E = n\,C\,N$, as before.

Measurement of Fluctuation.

The relative amount of fluctuation in the current furnished by a dynamo may be observed by noticing the inductive effect on a neighbouring circuit. Let a coil be introduced into the circuit, and let a second coil, wholly disconnected from the first, be laid coaxially with it, so that the coefficient of mutual induction between the coils shall be as great as possible. Introduce into the circuit of the second coil a Bell telephone receiver. If the main-circuit current is steady there will be no sound heard. If it fluctuate, each fluctuation will induce a corresponding secondary current in the telephone circuit, and the amount and frequency of the fluctuations may be estimated by the loudness and pitch of the sound in the telephone. The fluctuations of the current of a Brush dynamo, which are about 1½ per cent., are in this manner readily detected. Professor Ayrton has suggested the introduction into the secondary induction circuit of an electro-dynamometer to serve as a "discontinuity-meter."

Effect of Non-simultaneous Commutation.

If the brushes are not so set that the sliding of contact under one brush is not accomplished at the same instant as that under the other brush, then it is clear that there will be slightly unequal electromotive-forces in the two halves of the armature circuit. This momentary inequality will die out, to be succeeded by another inequality (of opposite sign) when commutation occurs at the other brush. The effect will be the same as though a small alternating current having 2 n c periods of alteration per second were made to act around the circuit of the armature. Such effects may be occasioned in armatures by various causes; if the number of sections in the armature be an odd number; if the numbers of conductors in all the sections are not alike or their connexions are unsymmetrical; or lastly, if the contact-edges of the brushes do not lie exactly at opposite ends of a diameter. These effects are independent of a still smaller alternation arising in every armature in consequence of mutual inductions between the currents in the commutated coils and those adjacent to them.

Measurement of **N**.

An important problem is how to measure the actual number of magnetic lines that pass through the armature. This number is really best ascertained by calculation from the performance of the machine itself. The speed being observed by aid of a suitable speed-counter, the number of conductors round the armature being known, and the whole electromotive-force generated in the machine being measured by proper electrical methods, then it only remains to apply the fundamental formula, transformed so as to calculate back to **N**:—

$$\mathbf{N} = \frac{E \times 10^8}{n\,C}.$$

To measure E the means adopted must depend upon the construction of the machine. If it is a continuous-current machine, either magneto or separately-excited, then a simple voltmeter applied at the open terminals or brushes will suffice. If the machine is series-wound or shunt-wound, the same method may apply, provided the magnetizing coils can be disconnected and separately excited up (for example, by using accumulators) to the right degree while the machine is run. In all these cases the result will not correctly represent the working values, because in work there are the reactions due to considerable currents in the armature coils. To measure E while the machine is running, it must either be run upon known resistances (so as to enable E to be calculated from Ohm's law); or E may be calculated by measuring (see p. 228) the difference of potentials at the brushes with a voltmeter, and then calculating from the resistance of and current in the armature the volts lost internally, which, added to the measured volts, make up the whole E.

Another way, which does not involve the running of the machine—and is therefore less satisfactory—is to wind closely around the armature, exactly in the diameter of commutation, a single turn of fine insulated wire, the ends of which are connected through two insulated wires lying close together, or, better, twisted together, to a ballistic galvanometer of slow period and of appropriate sensitiveness. This being done, arrangements are then made to separately excite the field-magnets, by some auxiliary current, to an amount equal to the working value. On turning on the exciting current, a current of short duration, proportional in its integral value to the number of magnetic lines which have thus been introduced through the wire loop, is excited in the circuit and produces a throw on the galvanometer; the amount of this throw can be regulated by introducing suitable resistances. On breaking the exciting circuit or short-circuiting the exciting coils, another throw is observed in the opposite direction, and of equal amount To ascertain the absolute number of lines indicated by this throw, a comparative experiment must be made with some sort of apparatus for introducing a known number of magnetic lines into the same circuit. A good way to do this is to use a hand-coil of large size (resembling on a large scale the coil of a tangent galvanometer), wound with a known number of turns of fine wire, the average area of these turns being known from careful measurement. Such a coil should be included in the circuit of the aforesaid galvanometer, but with leading wires enabling it to be placed at a sufficient distance away from the dynamo and from all other magnets and iron, to allow of no error arising from such causes of perturbation. It should be laid level in some spot for which the value of the vertical compound of the earth's magnetic field is known. (In London this is 0.43 C.G.S. units.) On suddenly inverting this coil, another throw is produced in the ballistic galvanometer. The result may be calculated out as follows:—Let δ_1 be the throw due to introducing the **N** lines through the loop, and δ_2 the throw given on inverting the coil. Calling the number of turns in the coil S, the (average) area of each of them A, and V the intensity of the vertical component of the earth's field, then the number of lines cut by inverting the coil is 2 S A V. And **N** is found by solving the simple rule-of-four sum:—

$$\mathbf{N} : 2\,S\,A\,V :: \delta_1 : \delta_2.$$

In a modification of this method, briefly described on p. 73, Mr. Mordey measures in an alternator the number of magnetic lines which pass at each position of the armature through its coils

THE MAGNETO-MACHINE AND THE SEPARATELY-EXCITED MACHINE.

In the equations hitherto considered it was assumed that the armature rotated in a magnetic field, the quantity of which was specified by the symbol **N**. Nothing was specified as to the kind of field-magnets; and the general formula deduced is of course applicable for all kinds, provided their magnetic power is known. In magneto-dynamos in which the field is due to permanent magnets of steel, **N** depends both on the magnetism of the steel and on the iron core of the armature. The number of lines that find their way through the armature is, however, lessened by the reaction of the armature when a large current is being drawn from the machine. If the magnetism of the field-magnets were so overpoweringly great, as compared with that due to the armature coils, that this reaction were insignificantly small, then, since our fundamental formula is:—

$$E = n\,C\,N,$$

E would, for any given magneto machine, be directly proportional to n, the speed of rotation. But we know in practice that this is not the case. Suppose we turn a magneto machine at 600 revolutions per minute ($n = 10$, for then there will be 10 revolutions per second) and get, say, 17 volts of electromotive-force from it, then, if there were no reactions from the armature, turning it at 1200 revolutions per minute ought to give exactly 34 volts. This is never quite attained; though in many machines, as, for example, in the laboratory-pattern magneto-Gramme machines made by Breguet (Fig. 7, p. 15), the direct proportion is very nearly attained even with much higher speeds.

Relation between Speed and Electromotive-force. Dead-Turns.

If the current in the armature is kept constant by increasing the resistances of the circuit in proportion to the speed, the demagnetizing action of the armature can be kept constant, even though the machine is giving out a current. In some experiments made by M. Joubert at different speeds, the electromotive-force was measured by an electrometer which allowed no current whatever to pass. The only possible reactions were those due to possible eddy-currents in the core: and the theoretical law was almost exactly fulfilled. The observations are given below, and plotted in Fig. 146, in which the straightness of the "curve" shows how nearly truly the theoretical condition was attained.[1]

Speed	500	720	1070	revolutions per minute.
Electromotive-force..	103	145	208	volts.

The departure from a straight line observed with high speeds is probably due to the demagnetizing effect of eddy-currents in the rotating masses.

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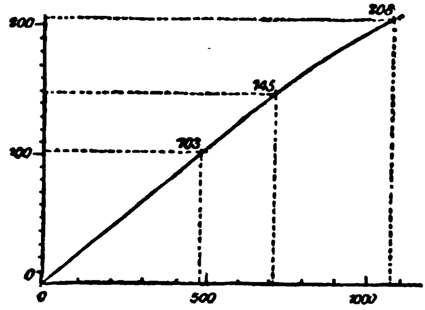
[1] See also experiments by Mordey, *Journal I.E.E.*, xix. 233, 1890.

The number of turns by which the speed, at any output, exceeds the number that would be needed for strict proportion is called the *dead-turns.*

FIG. 146.



CURVE SHOWING RELATION BETWEEN SPEED AND ELECTROMOTIVE-FORCE.

Potential at Terminals of a Dynamo. Lost Volts.

The potential at terminals of the magneto machine—and indeed of every dynamo—is, when the machine is doing any work, less than E, the total induced electromotive-force, because part of E is employed in driving the current through the resistance of the armature. The symbol e may be conveniently used for the difference of potential between terminals. Only when the external circuit is open, so that no current whatever is generated, $e = E$. It is convenient to have an expression for e in terms of the other quantities, seeing that when any current is being generated it is impossible to measure E directly by a voltmeter or by an electrometer, whereas e can always be so measured.

Let r_a be the internal resistance of the machine, that is to say the resistance of the armature coils, and of everything else in circuit between the terminals; and let R be the resistance of the external circuit. Then, by Ohm's law, if i be the current,

$$E = \cancel{(}i(r_a + R).$$

But by Ohm's law also, if e be the difference of potential between the terminals of the part of the circuit whose resistance is R,

$$e = i\,\mathrm{R};$$

whence

$$\frac{e}{\mathrm{E}} = \frac{\mathrm{R}}{r_a + \mathrm{R}}; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad [\mathrm{III.}]$$

also

$$e = \frac{\mathrm{R}}{r_a + \mathrm{R}}\,\mathrm{E}.$$

It is also convenient to note that

$$\mathrm{E} = \frac{r_a + \mathrm{R}}{\mathrm{R}}\,e;$$

for this formula enables us to calculate the value of E from observations of e made with a voltmeter. But often the values of R are unknown: hence the following is more useful. By subtracting the second of the above equations from the first of them we get:—

$$\mathrm{E} - e = i\,r_a$$

or

$$e = \mathrm{E} - i\,r_a \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad [\mathrm{IV.}]$$

This is equivalent to saying that the volts at the terminals are equal to the whole volts generated in the armature less the volts needed to drive the current i through the internal resistance r. The volts $i\,r_a$ which are thus not available in the external circuit, are called the *lost volts:* they will be less the smaller the internal resistance is. If e is observed by applying a voltmeter, then E can be found by adding to it the lost volts; and these can be calculated by measuring with an amperemeter the current flowing through the armature and multiplying this by the known internal resistance.

Relation between whole Electromotive-force and Difference of Potentials at the Terminals.

The essential distinction pointed out above between the whole electromotive-force E, and that part of it which is available as a difference of potentials at the terminals e, may be further illustrated by the following geometrical demonstration, which is due to Herr Ernst Richter.[1]

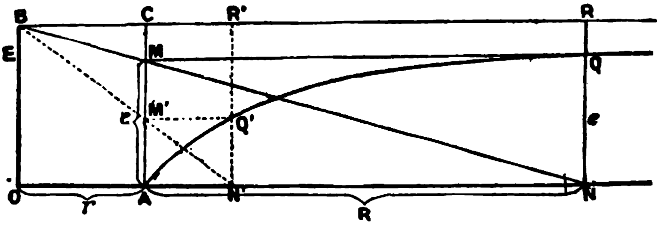
In a machine (such as are chiefly dealt with later) in which e is constant, E will not be constant, except in the unattainable case of a machine which has no internal resistance. Let r represent the internal resistance of the machine, including that of the armature and of any magnet-coils that are in the main circuit ($r = r_a + r_m$); then,

$$E = e + i\,r.$$

If E is constant, then e cannot be constant when i varies; and if e is constant, E cannot be. We have then two cases to consider:—

(1) E *constant.*—Take resistances as abscissæ and electromotive-forces as ordinates, and plot out (Fig. 147) O A = r,

FIG. 147.



A N = R, O B = E. The line B N represents the fall of potential through the entire circuit. Of the whole electromotive-force O B, a part equal to C M is expended in driving the current through the resistances r, leaving the part A M available as the difference of potential at the terminals, when the total resistance of the circuit is represented by the length from O to N. Accordingly, at N erect a vertical line N Q equal to A M. Take a less external resistance $R' = A\ N'$ and by a similar process we find that the corresponding value of e is A M′ or N′ Q′. Similarly, any number of points may be determined; they will all lie on the curve A Q Q′, which therefore shows how, as the external resistance is increased the terminal potential rises, whilst the whole electromotive-force remains constant and is represented by the ~~horizontal~~ vertical line ~~B R.~~ O B The equation of this curve is given by the condition

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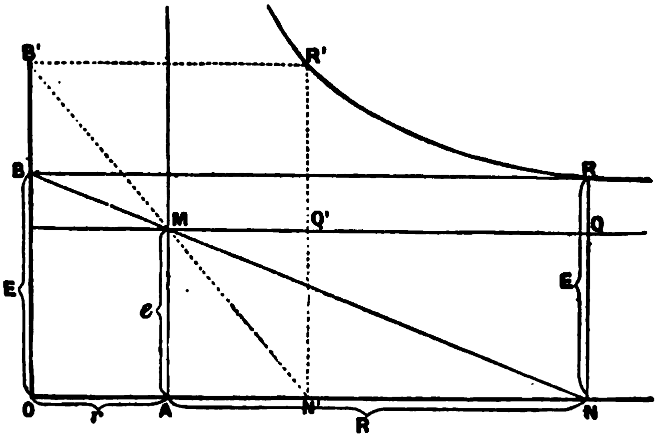
[1] *Elektrotechnische Zeitschrift*, iv. 161, April, 1883.

$$\frac{E - e}{E} = \frac{r}{R + r},$$

whence $(E - e)\ (R + r) = E\ r = \text{constant}$; which equation is the equation of an equilateral hyperbola having O B and B R as asymptotes.

(2) *e constant.*—As in the preceding case, $O\ A = r$; $A\ N = R$; and $A\ M = e$. From N (Fig. 148) draw the line

FIG. 148.



N M and produce it backwards to B. Then O B represents that value of E which will give e volts at terminals when R = ~~N M.~~ A N Accordingly set off at N the line $N\ R = O\ B$.

In a precisely similar way draw N′ B′, to correspond with any other value of R, and make N′ R′ equal to O B′. N′ R′ represents the value of E when the value of the external resistance R is equal to A N′. By determining other values we obtain the successive points of the curve R R′, which shows how the whole electromotive-force must vary in order to maintain a constant difference of potentials at the terminals, as represented by the ~~horizontal~~ vertical line ~~M Q~~ A M. The equation to this new curve is given by the condition

$$\frac{E - e}{r} = \frac{e}{R}$$

or

$$(E - e)\,R = e\,r = \text{constant}.$$

This curve is also an equilateral hyperbola.

The Separately-excited Dynamo.

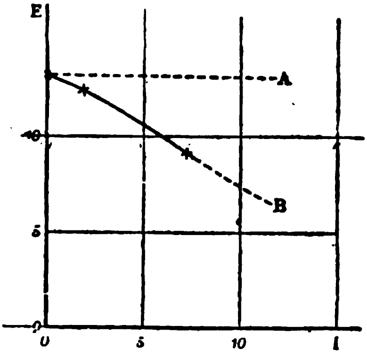
For separately-excited dynamos the same formulæ hold good as for magneto-dynamos; but in this case **N** depends upon the strength of the independent exciting current.

In estimating the nett (or commercial) efficiency of a separately-excited dynamo, the energy spent per second in exciting the field-magnets ought to be taken into account.

Characteristic of Magneto Machine, and of Separately-excited Dynamo.

In the magneto-dynamo the magnetism of the steel magnets is approximately constant. This has given rise to a common idea that in such machines the electromotive-force depends on the speed alone. This is not true. For owing to the cross-magnetizing and demagnetizing tendency of the currents in the armature coils, the number of magnetic lines that actually traverses the armature core diminishes when the currents in the armature are strong. The stronger the current in the armature the stronger the reaction. As will be explained (p. 245), it is convenient to plot out certain curves, known as *characteristics*, to exhibit the relation that subsists between the electromotive-force and the current under different conditions of speed, resistance, &c. Usually one of the conditions assumed is that the speed is constant. Such curves are particularly useful for studying the various reactions that exist between the field-magnet and armature. Fig. 149 gives the characteristic of a small magneto machine of the laboratory type, having a Gramme ring. It was capable of lighting two small Swan lamps of about 5 candle-power. On open circuit the electromotive force was 13·1 volts at a speed of 1400 revolutions per minute. The value of E, the total electromotive-force generated in the armature, fell from 13·1 to 12·4 volts when a current of 1·8 amperes was taken from the machine and when it was short-circuited to give 6·1 amperes the value of E fell to 9·2 volts. This was, however, an exceptionally bad case.

FIG. 149.



CHARACTERISTIC OF MAGNETO MACHINE.

The reaction of the armature current was here very strongly marked. Were there no reaction, the characteristic would follow the dotted line to A instead of dropping down to B. As explained on p. 89, the demagnetizing tendency of the armature current increases with the lead given to the brushes.

The characteristics of separately-excited dynamos exhibit a similar decline in the electromotive-force; and the reasons are exactly similar. A careful study of these machines was made in 1884 by Mr. W. B. Esson,[1] who gives the following curve for a separately-excited dynamo having a modified

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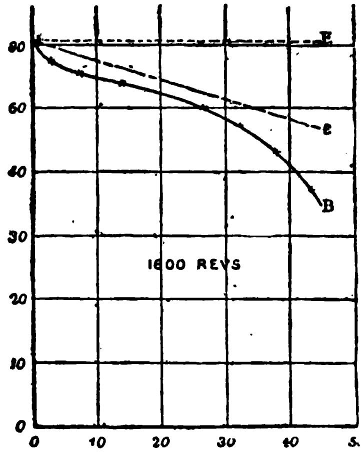
[1] *Electrical Review*, xiv. 393, April, 1884. See also papers by M. Marcel Deprez, *Comptes Rendus*, xciv. pp. 15 and 86, 1882.

Pacinotti ring armature. The line E (Fig. 150) represents the total electromotive-force if there were no reactions. The line *e* represents the values of the potential between the brushes of the machine (called *e* in this book in contradistinction to E the whole electromotive-force) as it would be if there were no reaction.

FIG. 150.



CHARACTERISTIC OF SEPARATELY-EXCITED DYNAMO.

The curved line B gives the actually-observed values of *e* when different currents were taken from the machine. The great drop at the lower end of the curve is probably due to the greater demagnetizing effect of the armature current when there is (as with strong currents) a considerable lead at the brushes. The characteristic always shows such downward curvature more when the field-magnets are weakly excited. (See Fig. 420.)

Efficiency and Economic Coefficient of Dynamos.

Suppose that we know the actual mechanical horse-power applied in driving a dynamo. This can be measured directly either by using a transmission dynamometer, or by taking an indicator diagram from the steam-engine that is driving it, or, in certain special cases where the field-magnets can be pivoted or counterpoised, by applying the method originally pursued by the Rev. F. J. Smith, and later described by M. Marcel Deprez and by Professor Brackett, in which the actual mechanical interaction between the armature and field-magnets is utilized to measure the horse-power used in driving the machine. If, then, we know the horse-power applied, and if we measure the "activity" of the dynamo, that is to say its output of electrical horse-power, we have by comparing the mechanical power absorbed with the electrical activity developed, a measure of the "efficiency" of the dynamo as an economical converter of mechanical energy into electrical energy. It must, of course, be borne in mind that part of the electrical energy developed is inevitably wasted in the machine itself, in consequence of the unavoidable resistance in the wire of the armature, and, in the case of self-excited dynamos, in the wire of the field-magnet coils. There must therefore be drawn the distinction mentioned on p. 117 between the gross efficiency of the machine, or as it is sometimes called, its "efficiency of electric conversion," and its nett efficiency or commercial efficiency.

To express efficiency, whether gross or nett, we must, however have the means of measuring the electric output of the dynamo, or of any part of its circuit.

As is well known, the energy per second of a current can be expressed, provided two things are known, namely, the number of amperes of current, and the number of volts of potential between the two ends of that part of circuit in which the energy to be measured is being expended. The number of amperes of current is measured by a suitable amperemeter; the number of volts of potential by a suitable voltmeter. The product of the volts into the amperes expresses the electric energy expended per second in terms of the unit of activity denominated the "watt" (see Appendix A, on Units). As 1 horse-power is equal to 746 watts, the number of volt-amperes (*i. e.* of watts) must be divided by 746 to give the result in horse-power. If i represents the current in amperes, and e the difference of potential in volts, then the "activity" or "electric power," for which we may use the symbol w, may be written

$$w = \frac{e\,i}{746}. \qquad \ldots\ldots \qquad [\text{V.}]$$

The ratio of the useful electrical energy realized in the external circuit to the total electric energy that is developed in the armature is called the "electrical efficiency" or "economic coefficient" of the machine. It may be expressed algebraically as follows:—If through an armature there is flowing a current of i_a amperes, and its total electromotive-force be E volts, then its total electric activity will be

$$= \mathrm{E}\, i_a \text{ (watts).}$$

If the volts of pressure between the terminals of the dynamo be e, then the useful activity is

$$= e\, i \text{ watts.}$$

Using the symbol η for the "economic coefficient," or so-called "electrical efficiency," we have

$$\eta = \frac{\text{useful activity}}{\text{total activity}} = \frac{e\, i,}{\mathrm{E}\, i_a},$$

or, if the machine has no shunt, so that i and i_a are the same thing,

$$\eta = \frac{e}{\mathrm{E}}.$$

But we know that the ratio $\frac{e}{\mathrm{E}}$ depends on the relation of the internal and external resistances, for

$$\frac{e}{\mathrm{E}} = \frac{\mathrm{R}}{r + \mathrm{R}} \text{ (see equation [III.]),}$$

where R is the resistance of the external circuit, and r the internal resistance (armature, magnets, &c.) of the machine. Hence, for a series dynamo or a magneto machine,

$$\eta = \frac{\mathrm{R}}{r + \mathrm{R}}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad \text{[VI.]}$$

Obviously, this coefficient will approach more and more nearly to *unity* the more that the value of r can be diminished. For if a machine could be constructed of *no* internal resistance there would be none of the energy of the current expended in driving the current through the armature and wasted in heating its coils.

We shall see later on how the expression for the economic coefficient η must be modified in the case of shunt dynamos and compound dynamos.

Returning now to the real efficiency of the machine, let us use the symbol W for the mechanical work-per-second, or horse-power, actually used in driving the armature. And, remembering that the gross electric activity of the machine is $\frac{\mathrm{E}\, i_a}{746}$, we have for the *gross efficiency*, or efficiency of electric conversion,

$$\frac{\mathrm{E}\, i_a}{\mathrm{W} \times 746},$$

and for the *nett efficiency*, or useful commercial efficiency,

$$\frac{e\, i}{\mathrm{W} \times 746}.$$

It will be seen that, as the first of these expressions contains E, and the second e, the nett efficiency can be obtained from the gross efficiency by multiplying by η, the economic coefficient.

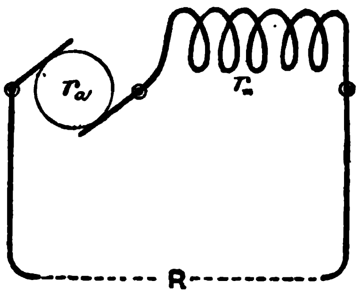
It must be noticed before passing from this topic that since i, the strength of the current, enters into each of the expressions for efficiency as a factor, and as i depends not only on the resistance of the machine itself, but on that of the lamps, or other parts of the system which it is used to feed, it is somewhat misleading to talk of the efficiency of the *dynamo*, as if the efficiency was a property of the dynamo. On the contrary, not only the gross efficiency, but also economic coefficient, and therefore *a fortiori*, the nett efficiency, depend on the external resistance, that is to say on the number of lamps that may happen to be alight! But still there is a sense in which these expressions are justifiable. Every dynamo is designed to furnish a certain quantity of lamps, and therefore to carry a certain average current. Its efficiency and coefficiency of economy ought therefore to be expressed in terms of that current (and of that external resistance) which may be considered the fair working load of the machine.

Variation of Economic Coefficient with Current.

It will be noticed that in the case of the series machine considered above, the value of η will be different when R the external resistance is varied. When R is very great compared with r, then the value of η is very nearly $\doteq 1$; but for small values of R, the value of η diminishes indefinitely. But when R is large the current is small, and when R is small the current is large. It appears, therefore, that a series dynamo has its maximum value for the economic coefficient when it is doing its minimum of work.

THE SERIES DYNAMO.

FIG. 151.



In the series dynamo (see Fig. 151, also Fig. 39), there is but one circuit, and therefore but one current, whose strength i depends on the electromotive-force E and on the sum of resistances in the circuit. These are:—

R = the external (variable) resistance.
r_a = the resistance of the armature.
r_m = the resistance of the field-magnet coils.

By Ohm's law—

$$E = (R + r_a + r_m)\, i.$$

Also e, the difference of potential between the terminals of the machine, is

$$e = R\, i.$$

It is also convenient to find an expression for the difference of potential between the brushes of the machine; the volts measured here being greater than e, because of the resistance of the field-magnets; and less than E, because of the resistance of the armature coils. For this difference of potential between brushes we will use the symbol ϵ. Then, by Ohm's law, remembering that the current running through r_m and R is of strength i, we have

$$\epsilon = (R + r_m)\, i\,;$$

whence, also,

$$e = E - (r_a + r_m)\, i.$$

Economic Coefficient of Series Dynamo.

From Joule's law of energy of current it follows that the economic coefficient η, which is the ratio of the useful electric energy available in the external circuit to the total electric energy developed, will be

$$\eta = \frac{\text{useful work}}{\text{total work}} = \frac{i^2 R\, t}{i^2 (R + r_a + r_m) t} = \frac{e}{E},$$

or

$$\eta = \frac{R}{R + r_a + r_m} \quad . \quad . \quad . \quad . \quad . \quad . \quad [\text{VII.}]$$

This is obviously a maximum when r_a and r_m are *both* very small. Sir W. Thomson recommends that r_m be made a little smaller than r_a.

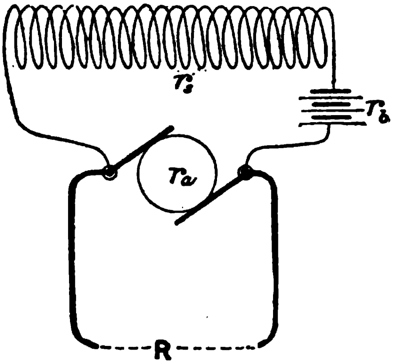
Example: In a Phœnix arc-lighting dynamo, designed by Esson, $r_a = 3{\cdot}448$ ohms, and $r_m = 4{\cdot}541$ ohms. If $i = 10$ amperes, the lost volts will be 79·89.

Further than this we cannot go without introducing some kind of an expression to connect E with the number of ampere-turns in the exciting coils. If we introduce the convenient approximate formula of Frölich, as given on p. 167, we shall obtain some approximate dynamo formulæ. These were given in detail on pp. 401 to 410 of the third edition of this book; wherein also, at pp. 620, 627, and 632, were given the more elaborate developments by Frölich, by Clausius, and by Rücker.

THE SHUNT DYNAMO.

In the shunt dynamo, there are two circuits to be considered; the main circuit, and the shunt circuit. The symbols used have the following meanings:

FIG. 152.



R = resistance of external main circuit (leads, lamps, &c.).
r_a = resistance of armature.
r_s = resistance of the shunt circuit (magnet coils).
i = the current in the external main circuit.
i_a = the current in the armature.
i_s = the current in the shunt circuit (the lost amperes).

Then, clearly,

$$i_a = i + i_s$$

because the current generated in the armature splits into these two parts in the main and shunt circuits, and is equal to their sum.

We may call that part of the whole current which returns through the shunt, and is not available in the external circuit, the *lost amperes:* in a good modern machine they are at most only 2 or 3 per cent. of the whole output of current. If e is the volts at the terminals, the lost amperes may be calculated as

$$i_s = e \div r_s$$

For example, in the Kapp dynamo (p. 488), giving 200 *amperes* at a pressure of 105 *volts* at terminals, r_s was 31 ohms, hence the *lost amperes* were 3·4, and total current in armature at full load 203·4 *amperes.*

Also, by Ohm's law, we have for e the electromotive-force between terminals,

$$e = \mathrm{R}\,i,$$

and also

$$e = r_s\,i_s;$$

because the terminals for the main circuit are also the terminals for the shunt circuit.

Further, since the nett resistance of a branched circuit is the reciprocal of the sum of the reciprocals of the resistances of its parts, the nett external resistance from terminal to terminal is equal to $\frac{\mathrm{R}\,r_s}{\mathrm{R} + r_s}$; and hence it follows that

$$\mathrm{E} = \left(r_a + \frac{\mathrm{R}\,r_s}{\mathrm{R} + r_s}\right) i_a.$$

We may at the same time find an expression for that part of the whole electromotive-force which is being employed solely to overcome the resistance of the armature, and which is, of course, the difference between E the total electromotive-force, and e the effective electromotive-force between terminals.

Ohm's law at once gives us

$$\mathrm{E} - e = r_a\,i_a,$$

or

$$\mathrm{E} - e = r_a\,(i + i_s).$$

From this we also get

$$e = \mathrm{E} - r_a\,(i + i_s). \quad . \quad . \quad . \quad . \quad [\mathrm{VIII.}]$$

We will also find an expression for E in terms of e, and the various resistances. Taking as above

$$\mathrm{E} = \left(\frac{\mathrm{R}\,r_s}{\mathrm{R} + r_s} + r_a\right) i_a,$$

and writing for i_a its value as $i + i_s$, and for these $\frac{e}{R}$ and $\frac{e}{r_s}$ respectively, we get

$$E = e\left\{\frac{R\,r_s + R\,r_a + r_a\,r_s}{R + r_s} \times \frac{R + r_s}{R\,r_s}\right\},$$

or

$$E = e \times r_a\left(\frac{1}{R} + \frac{1}{r_a} + \frac{1}{r_s}\right) \quad . \quad . \quad . \quad \text{[VIII. } bis.\text{]}$$

It may be noted that the expression $\left(\frac{1}{R} + \frac{1}{r_a} + \frac{1}{r_s}\right)$ is the sum of three conductivities of three paths, and is therefore equal to the conductivity of these three paths united in parallel with one another; that is to say, the conductivity as measured from brush to brush with the external circuit and shunt circuit joined up. Or, if we write $\mathfrak{R}$ for the resistance of the whole system of machine and circuit, as thus measured from brush to brush, then the equation may be written

$$E = e \times \frac{r_a}{\mathfrak{R}}.$$

Economic Coefficient of Shunt Dynamo.

The economic coefficient η, is the ratio of the useful electric energy available in the external circuit to the total electric energy developed.

By Joule's law there is developed in t seconds in the external circuit

$$\text{useful work} = i^2\,R\,t,$$

and in the same time there is wasted on heating,

$$\text{energy spent in shunt} = i_s^2\,r_s\,t,$$

and

$$\text{energy wasted in armature} = i_a{}^2\,r_a\,t;$$

whence

$$\frac{\text{useful work}}{\text{total work}} = \frac{i^2\,R}{i^2\,R + i_s{}^2\,r_s + i_a{}^2\,r_a}$$

$$=\frac{1}{1+\frac{\mathrm{R}}{r_s}+\frac{i^2 r_a+2\,i\,i_s r_a+i_s^2 r_a}{i^2\,\mathrm{R}}}$$

$$=\frac{1}{1+\frac{\mathrm{R}}{r_s}+\frac{r_a}{\mathrm{R}}+2\,\frac{i_s r_a}{i\,\mathrm{R}}+\frac{r_a}{\mathrm{R}}\left(\frac{i_s}{i}\right)^2}\,.$$

$$=\frac{1}{1+\frac{\mathrm{R}}{r_s}+\frac{r_a}{\mathrm{R}}+2\,\frac{\mathrm{R}}{r_s}\cdot\frac{r_a}{\mathrm{R}}+\frac{r_a}{\mathrm{R}}\left(\frac{\mathrm{R}}{r_s}\right)^2}$$

$$=\frac{1}{1+\frac{\mathrm{R}}{r_s}+\frac{r_a}{\mathrm{R}}+2\,\frac{r_a}{r_s}+\mathrm{R}\,\frac{r_a}{r_s^2}}$$

$$=\frac{1}{1+\frac{\mathrm{R}}{r_s}\left(1+\frac{r_a}{r_s}\right)+\frac{r_a}{\mathrm{R}}+2\,\frac{r_a}{r_s}}\,.$$

Now, for brevity, write for the total internal resistance, r_a+r_s, the single symbol r—

$$\eta=\frac{1}{1+\frac{\mathrm{R}\,r}{r_s\,r_s}+\frac{r_a}{\mathrm{R}}+2\,\frac{r_a}{r_s}}\,.$$

For this ratio to be a maximum it is clear that,

$$\frac{d\left(1+\frac{\mathrm{R}}{r_s}\cdot\frac{r}{r_s}+\frac{r_a}{\mathrm{R}}+2\,\frac{r_a}{r_s}\right)}{d\,\mathrm{R}}\text{ must }=0,$$

or

$$\frac{r}{r_s^2}-\frac{r_a}{\mathrm{R}^2}=0\,;$$

whence

$$\mathrm{R}^2=\frac{r_a r_s^2}{r}=r_a r_s\frac{r_s}{r},$$

and

$$\mathrm{R}=\sqrt{r_a r_s}\sqrt{\frac{r_s}{r}}, \quad . \;\; . \;\; . \;\; . \;\; . \;\; . \;\; . \;\; . \quad [\mathrm{IX.}]$$

or

$$\mathrm{R}=r_s\sqrt{\frac{r_a}{r}} \quad . \;\; . \;\; . \;\; . \;\; . \;\; . \;\; . \;\; . \;\; . \quad [\mathrm{IX}a.]$$

R

This equation determines what particular resistance of the external main circuit will give the best economy with given internal resistances. Now substitute this value in those terms of the equation for η which contain R, and we get as their values:—

$$\frac{\mathrm{R}r}{r_s^2} = \frac{r}{r_s}\sqrt{\frac{r_a}{r}} = \frac{\sqrt{r_a r}}{r_s},$$

$$\frac{r_a}{\mathrm{R}} = \frac{r_a}{r_s}\sqrt{\frac{r}{r_a}} = \frac{\sqrt{r_a r}}{r_s};$$

whence

$$\eta = \frac{\text{useful work}}{\text{total work}} = \frac{1}{1 + 2\frac{\sqrt{r_a r}}{r_s} + 2\frac{r_a}{r_s}}$$

This may be still further simplified, for we know that the resistance of the shunt is very high compared with that of the armature, possibly from 300 to 1000 times as great. If, then, $\frac{r_a}{r_s}$ is so small a term in comparison with the other term as to be negligible, we get

$$\eta = \frac{1}{1 + 2\frac{\sqrt{r_a r}}{r_s}}; \quad \ldots\ldots\ldots \quad [\text{X.}]$$

and since r_a is small compared with r_s, r is very nearly equal to r_s, so that we may write, as an approximate equality,

$$\eta \doteqdot \frac{1}{1 + 2\frac{\sqrt{r_a r_s}}{r_s}};$$

or

$$\eta \doteqdot \frac{1}{1 + 2\sqrt{\frac{r_a}{r_s}}} \quad \ldots\ldots\ldots \quad [\text{XI.}]$$

This latter approximate value is identical with that given by Sir W. Thomson in the report of the British Association for 1881: the equation No. [X.] is, however, more correct.

It may be pointed out that it follows from equation No. [IX.] above, that when the resistance of the armature is small compared with that of the shunt, so that r_s may be taken as equal to the value of r (which would be highly desirable if it could be attained in practice), then we should have

$$R = \sqrt{r_a r_s}; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad [\text{XII.}]$$

that is to say, when the proportion between r_a and r_s is made as favorable as possible, then the best external resistance to work with from the economic point of view is that resistance which is a geometric mean between the resistances of the armature and of the shunt coils, and any departure from this will diminish the value of the economic coefficient.

Practical Rules for Economic Design.

This affords us some practical information how to apportion the resistances in a shunt dynamo. Let the question be thus stated. Given the resistance of the armature r_a, what must the shunt resistance be so that the dynamo may (under favorable proportions of external resistance R) have an economic coefficient of 90 per cent. From equation [XI.] we get

$$\frac{90}{100} = \frac{1}{1 + 2\sqrt{\frac{r_a}{r_s}}}$$

$$\frac{100}{90} = 1 + 2\sqrt{\frac{r_a}{r_s}},$$

$$10 = 180\sqrt{\frac{r_a}{r_s}},$$

$$r_s = (18)^2\, r_a,$$

$$r_s = 324\, r_a.$$

No shunt machine can give in the external circuit as much as 90 *per cent. of its total electric energy unless its shunt has a resistance at least* 324 *times as great as that of its armature.*

A good practical rule would be the following:—Ascertain what number of lamps will be the usual full load: reckon the resistance of them when connected to the mains. Let the armature resistance be one-twentieth of this; and let the shunt resistance be twenty times as great as this. In this case about 4 per cent. will be wasted in the armature, and about 4 per cent. in the shunt, leaving a margin of a little over 90 per cent. for the economic coefficient.

In a shunt machine described by Sir C. W. Siemens in the *Philosophical Transactions*, 1880, the results were:—

——	Armature.	Shunt Magnet.	r_s/r_a.	η observed per cent.
Siemens	0·204	11·26	48·4	69·0

In an Edison machine ("K," 250 lights) tested at Munich the values were:—

——	Armature.	Shunt Magnet.	r_s/r_a.	η observed.
Edison, "K"	0·0361	13·82	382·8	88·6

The Edison-Hopkinson machine, described on p. 520, gave:—

Resistance when cold	0·009947	16·93	1702	93·66

The Kapp dynamo alluded to above, p. 230, and depicted in Plates I. & II., gave, including the series coil with the armature:

(Cold)	0·0306	29·133	952	92
(Warm)	0·0329	31·08	945	

CHAPTER X.

CHARACTERISTIC CURVES.

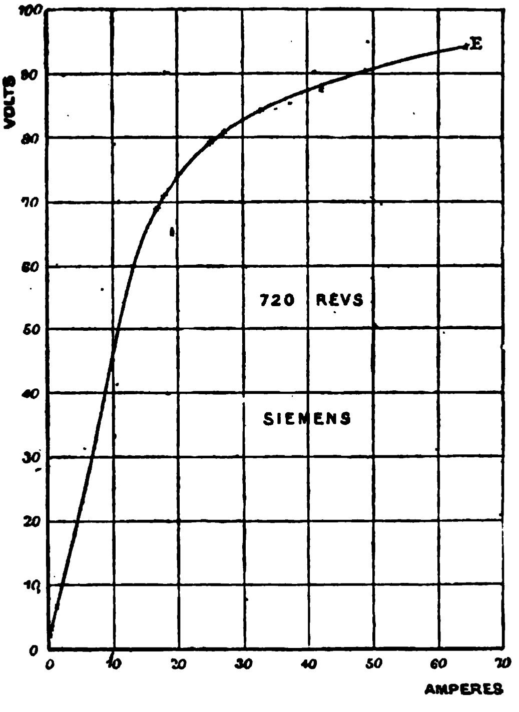
So many practical problems in the construction of dynamo-electric machines are in the present state of science solved by the use of graphic diagrams, and particularly by the use of certain curves technically called *characteristics*, that the method of constructing and using them forms an important part of the theory of the dynamo. For many practical purposes no other method is half so useful.

The characteristic curve stands indeed to the dynamo in a relation very similar to that in which the indicator diagram stands to the steam-engine. As the mechanical engineer, by looking at the indicator diagram of a steam-engine, can at once form an idea of the qualities of the engine, so the electrical engineer, by looking at the characteristic of the dynamo can judge of the qualities and performance of the dynamo. The comparison may even be said to reach further than this.

The steam-engine indicator diagram serves two purposes which, though not unconnected with one another, are yet distinct. When the scale on which the diagram is drawn is known, it gives direct information as to the horse-power at which the engine is working, depending on the total area enclosed by the curve, and quite irrespective of its form. But even though the actual scale be not known, the details of the form of the curve at its various points give very definite information to the engineer as to the working of the engine, the perfection of the exhaust, the setting of the valves, the efficiency of the cut-off, and the adequacy of the supply pipes and port-holes of the valves.

So also the characteristic curve of the dynamo may serve two functions. When the scale on which it is drawn is known it tells the horse-power at which the dynamo works; nay, can indicate at what horse-power the dynamo may be worked to the greatest profit. But even though the actual scale be not known, the details of the form of the curve afford definite information as to the conditions of the working of the machine; the degree of saturation of its magnets, the sufficiency of the field-magnets in proportion to the armature, and the goodness of the design in several respects.

FIG. 153.



CHARACTERISTIC CURVE OF A SERIES DYNAMO.

The suggestion to represent the properties of a dynamo machine by means of a characteristic curve is due to Dr. Hopkinson, who in 1879 described such curves to the Institution of Mechanical Engineers, and gave the curve of the Siemens dynamo reproduced in Fig. 153. The name of "characteristic" was assigned in 1881 by M. Marcel Deprez[1] to Hopkinson's curves; and the excellence of the name has been attested by its general adoption.

Dr. Hopkinson's object was to represent the relation subsisting between the electromotive-force and the current; he therefore constructed from observations a curve in which the abscissæ measured horizontally represent the number of amperes of current flowing, and the vertical ordinates the corresponding values of the electromotive-force. The following table (taken with some trifling modifications from Dr. Hopkinson's paper in the *Proceedings of the Institution of Mechanical Engineers*, 1879, p. 249) gives the observed values of i the strength of the current, and E the electromotive-force, of a certain series-wound dynamo.

EXPERIMENT ON SIEMENS DYNAMO AT SPEED OF 720 REVOLUTIONS PER MINUTE.

Current (in amperes). i	Resistance (in ohms). R	Electromotive Force (in volts). E
0·0027	1025	2·72
0·48	8·3	3·95
1·45	5·33	7·73
16·8	4·07	68·4
18·2	3·88	70·6
24·8	3·205	79·5
26·8	3·025	81·1
32·2	2·62	84·4
34·5	2·43	83·8
37·1	2·28	84·6
42·0	2·08	87·4

It may be remarked that the electromotive-force E is the total electromotive-force generated in the machine, and must not be confounded with e the difference of potential between the terminals as measured by a voltmeter, or other similar instrument. In many cases we now prefer to plot *e* instead of E; but that was not Hopkinson's original method. He determined E by measuring *i* and multiplying it by the total resistance of the circuit; for by Ohm's law i R = E. It should also be remarked that the dynamo was a "series dynamo," shunt-wound machines not having at that date come into vogue.

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[1] Vide *La Lumière Electrique*, Dec. 3, 1881; where however, Deprez gives a method of observation that is open to the objection that it neglects the armature reactions.

Before entering into other points, it may be worth while to consider the meaning of the curve. It begins at a point a little above the origin. This shows that there was a small amount of residual magnetism remaining permanently in the field-magnets. The curve ascends at first at a steep angle, then curves round and eventually assumes a nearly straight course, but at a gentler slope than before. Whence arise these typical forms? It is known that electromotive-force of a dynamo depends not only on the speed of running and on the number of coils of wire in the armature, but also on the intensity of the magnetic field. Now if the speed is constant—it was maintained at 720 revolutions per minute in Hopkinson's experiments—the only variable of importance is the intensity of the magnetic field. As the magnetism of the field-magnets rises and grows towards its maximum, the intensity of the field also rises and grows toward a maximum, and so does the induced electromotive-force. We might therefore expect, as Hopkinson points out, that the curve which represents the relation between the current and the electromotive-force of the series-wound dynamo should exhibit peculiarities of form similar to those of the curve which represents the relation between the magnetizing current and the magnetization of an electromagnet; and a comparison of Fig. 153, the "characteristic" of the dynamo, with Fig. 92, the "magnetization curve" of an electromagnet, will suffice to reveal the analogy. It must, however, be pointed out that the intensity of the field does not depend only on the strength of the field-magnet, but is affected by the current that is circulating in the armature coils in consequence of the reaction between the field-magnets and armature. Moreover, certain prejudicial effects arising from self-induction in the armature coils come into play with high speeds and strong currents, and prevent the electromotive-force from being proportional to the strength of the field. Hopkinson's statement that the characteristic of the dynamo may also be taken to represent the magnetization of the field-magnet, cannot therefore be accepted except with the reservation that it is true only when these reactions are negligibly small, which is seldom the case.

It is possible for a dynamo to be made to draw its own characteristic by mechanically moving the pencil relatively to the paper (as in steam indicators) by means of two electromagnets, one of them being excited by the main current, the other being connected as a shunt to the terminals of the machine.

Dr. Hopkinson, in the paper alluded to, and in a second one published in the *Proc. Inst. Mech. Engin.*, in April, 1880, p. 206, pointed out a great many of the useful deductions to be drawn from a consideration of these curves. Some other deductions have been made by M. Marcel Deprez, for which the reader is referred to *La Lumière Electrique*, of Jan. 5th, 1884. Dr. Frölich has also published several important papers on the subject in the *Elektrotechnische Zeitschrift* for 1881 and 1885. Dr. Hopkinson has returned to the subject in a lecture before the Institution of Civil Engineers, "On Some Points in Electric Lighting," April, 1882.

Horse-power Characteristics.

As mentioned at the beginning of this chapter, if the characteristic curves are drawn to scale the activity of the dynamo may be read off from them in horse-power. The product of the current into the potential is proportional to the rate at which the electric energy is being evolved. The product of one volt of potential into one ampere of current is sometimes called one *volt-ampere*, and has also been called by the special name of one *watt*. One watt or volt-ampere is equal to $\frac{1}{746}$ of a horse-power. To calculate the horse-power (electrical) evolved in the circuit when the dynamo is running at any particular speed, with a particular number of lamps in circuit, two measurements have ordinarily to be made—the volts of electromotive-force and the amperes of current. These must then be multiplied together and divided by 746 to obtain the horse-power. But if the characteristic of the dynamo at the particular speed be known, a reference to the curve will show at once what the electromotive-force is that corresponds to any particular current. For example, in the Siemens dynamo examined by Hopkinson, the characteristic of which is given in Fig. 153, p. 246, suppose the dynamo was working through such a resistance as to give 30 amperes when running at 720 revolutions, we see at once that the corresponding electromotive-force is 83. Hence

$$\frac{83 \times 30}{746} = 3 \cdot 3 \text{ horse-power.}$$

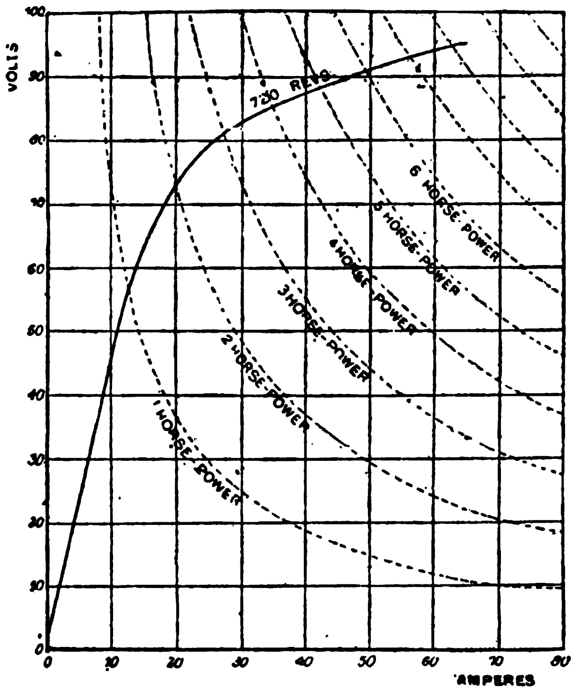
Now to obviate such calculations we may plot out on the diagram some additional curves crossing the characteristics and mapping them out into equal values of horse-power. These "horse-power lines" are nothing else than a set of rectangular hyperbolas. For example, the 1-horse-power line will pass through all the points for which the product of volts and amperes is equal to 746. It will therefore pass through the point corresponding to 74·6 volts and 10 amperes; through 37·3 volts and 20 amperes; through 14·92 volts and 50 amperes, &c., because the products in each of those cases is equal to 746 watts or 1 horse-power. The 2-horse-power line will pass through points whose product values are equal to 746 × 2, and the other lines in the same way. Fig. 154 shows the characteristic of the Siemens machine, reproduced from Fig. 153 above, but with the horse-power lines added.

In this case the volts plotted are the total electromotive-force "E," of the dynamo, and therefore the horse-power represents the total electric energy converted per second in the circuit of the dynamo. If instead of E we had plotted the values of "*e*," the difference of potentials between the terminals, we should have had a slightly different curve, representing the amount of electric energy appearing per second in the external circuit and available for useful purposes.

A horse-power characteristic of a shunt-wound dynamo is given further on, in Fig. 162.

If the vertical and horizontal scales are not chosen equal, the horse-power lines, though hyperbolæ, are of course distorted. X This is a mistake

FIG. 154.

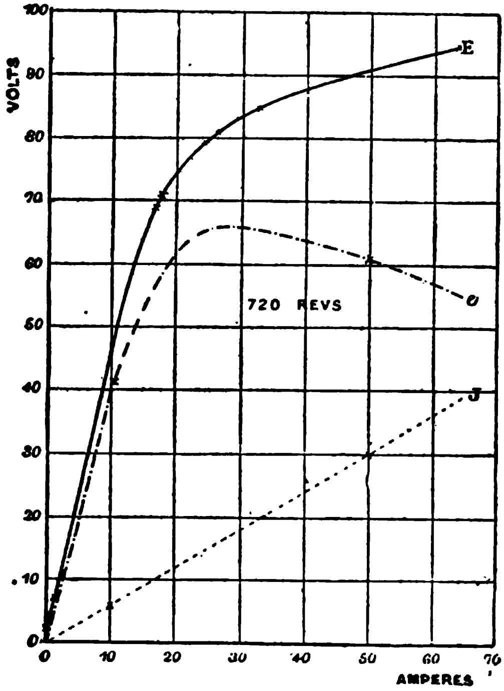


CHARACTERISTIC WITH HORSE-POWER LINES.

"*External*" *Characteristics or Terminal Potential Curves.*

For many purposes it is more useful to know the relation between the current and the "external" difference of potential at the terminals than to know the relation between the current and the whole electromotive-force induced in the armature; and it is mostly easier to measure e than to measure E, seeing that while the former can be directly measured with a voltmeter, the latter can only be got at indirectly. The name *external characteristic* may be given for the sake of distinction to those curves which exhibit the relation between the potentials and the currents of the external circuit. In the series dynamo it is a simple matter to derive one of these curves from the other, provided the internal resistance of the machine (armature and field magnets) is known. In the Siemens dynamo examined by Hopkinson in 1879, and of which Figs. 153 and 154 give the total characteristic, the total internal resistance was 0·6 ohm. The curve is reproduced for a third time in Fig. 155, where it is marked "E." Now to force a current of 10 amperes through a resistance of 0·6 of an ohm would require a difference of potential of 6 volts between its terminals. Looking at the curve, we see that the whole electromotive-force, corresponding to 10 amperes, was about 46·5 volts. Of this number, 6 were employed, as mentioned, in overcoming the internal resistance, leaving 40·5 volts as the available potential between terminals. Further, when the current was running at 50 amperes, there must have been no less than 30 volts *lost* in overcoming the internal resistance of 0·6 ohm; and as the value of E for this current is 90·5 volts, there remain 60·5 volts for *e*. There are now two ways open to us of representing these matters on our diagram. They are both shown in Fig. 155. The line J is drawn through the origin, and through the values of 6 volts for 10 amperes and 30 volts for 50 amperes. (The tangent of the slope of the line J is equal to $6 \div 10 = 0 \cdot 6$. We shall see later that this slope represents the internal resistance.) Then if the heights of the ordinates from the base line up to the line E represent total volts induced, and if the heights of the ordinates from the base line up to the line J represent the corresponding volts lost in overcoming internal resistance, it follows that *the difference of potentials at the terminals will be represented by the differences of the ordinates between the lines* J *and* E. This is the first way of representing those differences of potentials. The second way is to cut off from the tops of the ordinates portions equal to those of the line J. This amounts to subtracting the internal volts, which as shown in the algebraic theory are equal to $i\ (r_a + r_m)$, from E, and so obtaining the values of *e*. These are plotted out in the curve marked "*e*" in the figure; and as this curve represents the available electromotive-force in the external circuit, it obtains the name of *external characteristic* or terminal potential curve. As a matter of fact it is more usual to reverse the operation. The terminal potential values are easily observed with a voltmeter and the current with an ampere-meter. Then the external curve for *e* and *i* is plotted; and by *adding* to the ordinates the corresponding values of the lost volts, and so obtaining the curve for E and *i*. If there is permanent magnetism in the magnets, the characteristics will not start from the origin, but from a point a little above it.

G. 155.

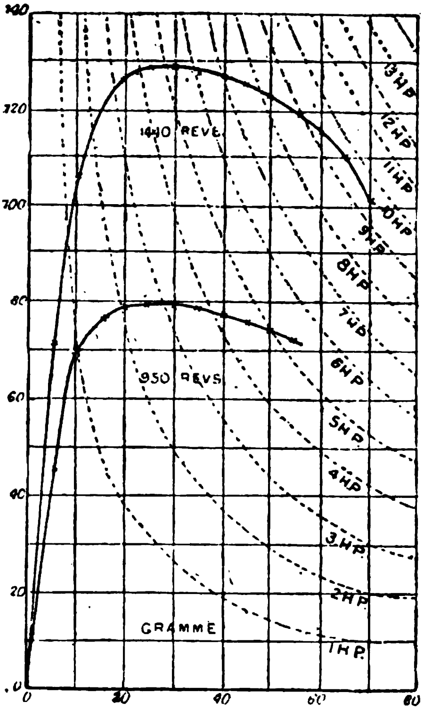


TOTAL AND EXTERNAL CHARACTERISTICS.

Characteristics of Series Dynamo.

The Siemens dynamo of which the characteristic is given in Fig. 153 was a series dynamo. For the sake of comparison the characteristic is given in Fig. 156, of an "A" Gramme machine also series-wound. This machine had, when it was measured by M. Marcel Deprez, 0·41 ohm resistance in the armature coils and 0·61 ohm in the coils of the field-magnets. Two characteristics are given; one corresponding to a speed of 1440, the other to a speed of 950 revolutions per minute. The horse-power lines are shown in dot also. The figures are given in the following table.

FIG. 156.



CHARACTERISTIC AT DIFFERENT SPEEDS.

EXPERIMENTS ON GRAMME SERIES-WOUND DYNAMO.

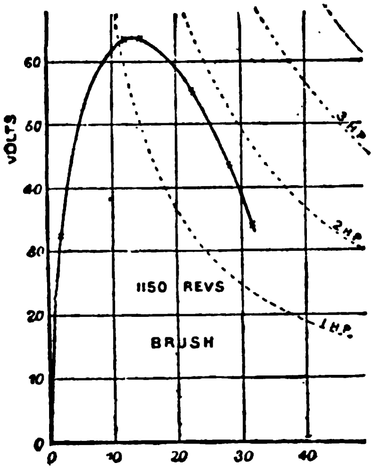
Current (in amperes).	Electromotive Force (in volts).	
	Speed 1440.	Speed 950.
5	72	45
10	107	70
15	122	77
20	127	79
25	129	79
30	128	79
35	128	79
40	127	78
45	125	76
50	123	74
55	120	72
60	116	—
65	110	—
70	101	—

In the series dynamo the magnetization of the magnets increases with the current, and therefore, at first, the electromotive-force increases also, giving the first straight portion of the curve. As the magnets approach saturation the curve turns, and, as the reactions due to the current in the armature now become of relatively great importance, flattens itself and ultimately turns down again.

One circumstance that contributes to the diminution of the electromotive-force when large currents are passing through the armature, is that if the field-magnets are relatively not powerful, the cross-magnetizing effect of the armature current causes a great displacement of the neutral point, and obliges a considerable lead being given to the brushes, with the result that the demagnetizing effect of the armature on the field-magnets (p. 89) becomes greatly increased. The dip in the characteristic is always greater in the case of weak field-magnets. It also occurs most in those machines in which the core of the armature is more nearly saturated than the cores of the field-magnets; for when with large currents the armature cores get saturated, the magnetic leakage from the pole-pieces becomes relatively greater.

One more curve of a series-wound dynamo is given in Fig. 157. This is a small Brush machine (intended to supply a single arc light) of the old pattern, with solid iron ring, in which, owing to the peculiar arrangement of the coils (see p. 458), the reactions of the armature make themselves known by a very extraordinary down-bending of the characteristic. This is partly due to the arrangements for cutting out a pair of coils as they approach the neutral point. It will be noticed that the maximum horse-power of this small machine is 1¾ horse; and that this value is only obtained when the reactions have already set in. The remarkable diminution in the electromotive-force which takes place when the machine is so treated as to demand from it an output which it was never intended to give, is in practice a real advantage. Should the machine be accidentally short-circuited while running, the reactions of the armature prevent the production of an injuriously large current, which might overheat the coils. It is considered an advantage in machines for arc-lighting, where a nearly constant current is required, to employ machines with drooping characteristics, and to work them at this part of the curve.

FIG. 157.



DROOPING CHARACTERISTIC.

Relation of Characteristic to Speed.

We know that the electromotive-force generated in a rotating coil or armature would be strictly proportional to the intensity of the magnetic field, were it not for the reactions of the current in the armature. Now in a series dynamo, the intensity of the field depends on the strength of the current; and, if the current is kept constant (by adjusting the resistances), the intensity of the magnetic field will also be constant even though the speed of the armature be varied. If therefore the characteristic of a machine be known at any speed, its characteristic for any other speed can be found by the very simple process of increasing the ordinates of the curve in a similar proportion. Take, for example, the case of the Gramme dynamo, of which a characteristic at the speed of 950 revolutions is given in Fig. 156. The characteristic at 1440 could be calculated from it by increasing the ordinates in the proportion of $\frac{1440}{950}$. Thus we see from the lower curve that when the current was 20 amperes the electromotive-force was 79 volts. Then $79 \times 1440 \div 950 = 119{\cdot}7$ volts. The actual electromotive-force observed at the speed of 1440 and with current at 20 amperes was 127 volts. There is a slight discrepancy here, and indeed always; for dynamo machines behave invariably as if a certain number of the revolutions did not count electrically. If the number of "dead turns" (see p. 226) were here reckoned as 140, the number of volts calculated by theory would agree very exactly with that observed.

RESISTANCE IN THE CHARACTERISTIC.

In the characteristic we have volts plotted vertically and amperes horizontally. Now by Ohm's law, volts divided by amperes give ohms. How can this be represented in the characteristic? Suppose, for example, it is required to represent the resistance of the circuit corresponding to some particular current. Let Fig. 158 be the characteristic of the dynamo in question, and it is desired to know what is the resistance corresponding to the state of things at the point marked P. Draw the vertical ordinate P M, and join P to the origin O. The line P O has a certain slope, and the angle of its slope is P O M. Now P M is equal to the electromotive-force under consideration, and O M is the current. Therefore, by Ohm's law,

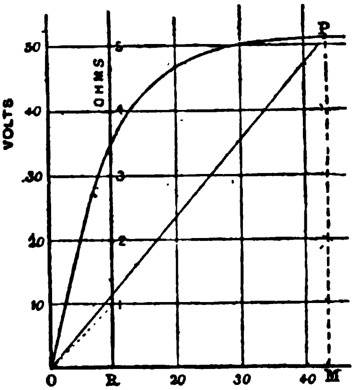
$$\text{Resistance} = \frac{\text{electromotive-force}}{\text{current}} = \frac{\text{P M}}{\text{O M}};$$

but

$$\frac{\text{P M}}{\text{O M}} = \tan \text{P O M};$$

therefore the resistance = tan P O M. Put into words, this is:—*The resistance corresponding to any point on the characteristic is represented in the characteristic by the trigonometrical tangent of the angle made by joining the point to the origin.* An easy way of reckoning these tangents is shown in Fig. 158. At the point on the horizontal line corresponding to 10 amperes erect a vertical line. A line drawn from the origin at an angle whose tangent is = 1 (namely 45°) would cross this vertical line at a point opposite the 10-volt mark. This point may then be called 1 ohm, and equal distances measured off on this line will constitute it a scale of resistances. In Fig. 158 the resistance corresponding to point P of the characteristic is seen to be about 1·2 ohm on the scale of resistances. Now P is placed at 51·3 volts, and the current is 43·2 amperes. Dividing one by the other, we get 1·18 ohm. Such calculations are then obviated by the graphic construction.

Fig. 158.



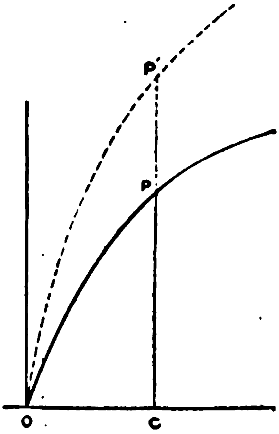
Method of Representing Resistance Graphically.

If in the actual dynamo the resistance of the circuit were gradually increased, we should have the point P displaced along the curve backwards towards the origin, the volts and amperes both falling off, and the steepness of the line O P increasing. When O P arrived at a certain steepness it would practically form a tangent to that part of the characteristic which is nearly straight, and then any very small increase in the resistance would cause the dynamo to lose its magnetism, from lack of current to magnetize the magnets. The resistance may be similarly represented on the characteristics of shunt dynamos (see Fig. 162); but in this case if the characteristic is drawn for the external current and the external difference of potential, then the resistance so represented will be the external resistance.

RELATION OF CHARACTERISTIC TO WINDING OF ARMATURE AND FIELD-MAGNETS.

Suppose the armature of a machine to be re-wound with a larger number of turns of proportionally thinner wire. What will be the result when rotated at the same speed as before? The resistance will be increased somewhat, and the electromotive-force also will be higher. Let Fig. 159 represent the characteristic of the machine as it was when there were X turns of wire on the armature. How must it be drawn when the number is increased to X′? Let P represent a point corresponding to a certain strength of current. Taking the new armature, let the resistance be varied until the current once more comes to the same value. The magnets are now magnetized exactly as strongly as before; but there are X′ turns of wire cutting the lines of magnetic force instead of X. The electromotive-force will therefore also be greater in the proportion of $\frac{X'}{X}$ Draw therefore P′ C so as to have the proportion P′ C : P C : : X′ : X. All other points on the new

FIG. 159.

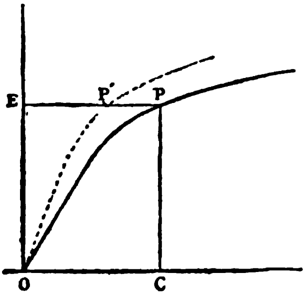


characteristic can be obtained by similarly enlarging the ordinates in the same ratio.

It will be evident from this that increasing the number of turns of wire in the armature has the same effect as increasing the speed of driving. This shows that *slow speed* dynamos (as required for use on ships, &c.) may be made to give the requisite electromotive-force provided the number of turns of wire be relatively increased. This involves, however, a sacrifice of economy, because of the increase of resistance in the armature.

The effect of altering the number of turns of wire on the field-magnets can also be traced out on the characteristic diagram. Suppose the number of turns in the magnetizing coil be S, and that we re-wind the machine, increasing the number to S′ turns. What will the result be? In this case we shall get the same electromotive-force when driving at the same speed as before, provided the magnets be equally magnetized. But if the current goes S′ times round instead of S we shall want a current only $\frac{S}{S'}$ as strong as before, to produce the same magnetization. To get the new characteristic then (see Fig. 160), draw P E horizontally. P E = C O = the current corresponding to electromotive-force E. Find P′ such that P′ E : P E : : S : S′; then the new characteristic will pass through P′. Similarly, all other points of the new characteristic may be determined by reducing their abscissæ in a similar proportion.

Fig. 160.

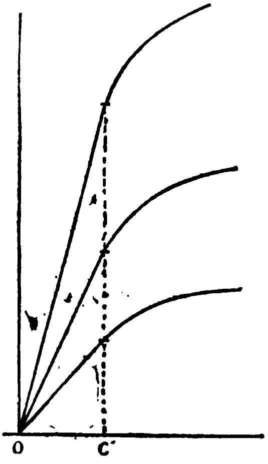


It must be noted that these two processes are not admissible for the characteristics of shunt-wound machines.

CRITICAL CURRENT OF SERIES DYNAMO.

From the fact that the characteristics for different speeds differ only in the relative scale of the ordinates, an important consequence may be deduced. The first part of every characteristic for any speed is nearly straight up to a point where for that speed the electromotive-force is nearly two-thirds of its maximum value. When the current is such that the electromotive-force has attained to this value, any very small change either in the speed of the engine or in the resistance of the circuit produces a great change in the electromotive-force, and therefore in the current; therefore, since this critical case occurs always with the same current (see Fig. 161), this current—corresponding to the point on all the curves where the straight line begins to turn—may be called the "critical current" of the dynamo. Each series dynamo has its own critical current, and it will not work well with a less one; for a less one will not adequately excite the field-magnets. It will further be seen that since with each speed the characteristic rises with a corresponding slope, there will be one particular resistance at each value of the speed at which the critical current will be obtained, and the higher the speed the higher may be the resistance. There is no such thing as a critical resistance in a series dynamo: for whether a resistance is critical or not depends upon the speed. *Neither is there any such thing* per se *as a critical speed for a series dynamo;* for whether the speed is critical or not depends on the resistance of the circuit.

FIG. 161.

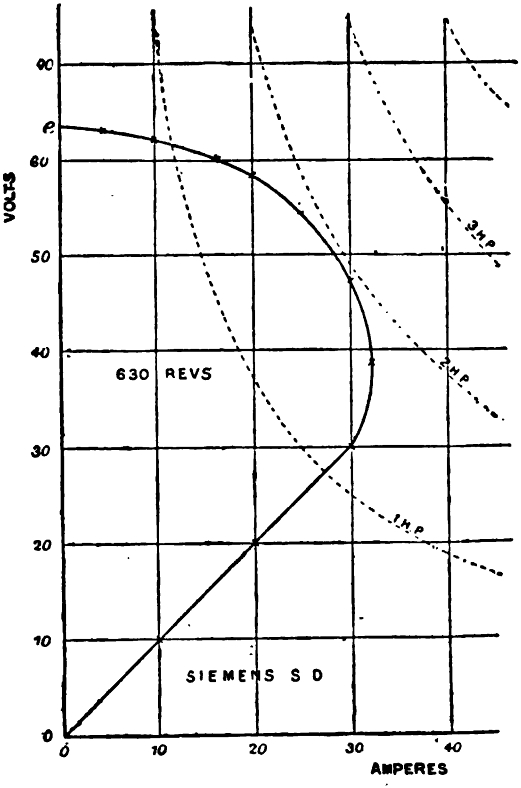


CHARACTERISTIC OF SHUNT DYNAMO.

For the shunt dynamo there are two separate characteristics the *external characteristic*, in which the quantities plotted are the amperes of current in the external circuit and the volts of potential between terminals; and the *internal characteristic* in which the volts and amperes of the shunt circuit are plotted. The internal characteristic of the shunt dynamo is quite similar to the external characteristic of a series dynamo, and shows the saturation of the field-magnets. It is better to plot it with ampere-turns instead of amperes, because the magnetization depends on the number of turns in the coil as well as the amperes.

The external characteristic of a Siemens shunt dynamo (the same described by the late Sir William Siemens before the Royal Society in 1880, and by Mr. Alexander Siemens in the *Journ. Soc. Teleg. Eng.*, March 1880) is given in Fig. 162,

FIG. 162

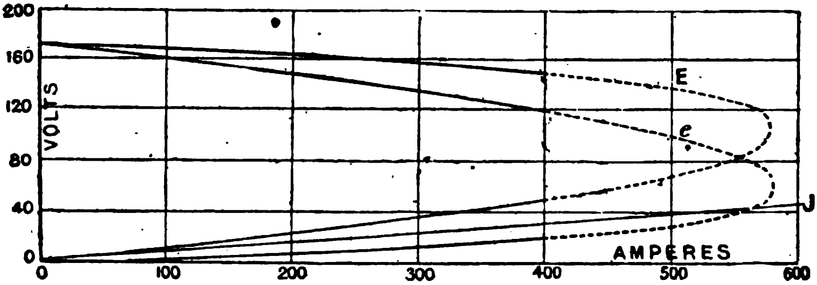


EXTERNAL CHARACTERISTIC OF SHUNT DYNAMO.

and the horse-power lines are shown dotted. The utmost power of this machine at 630 revolutions was just under 2 horse-power with a current of 30 amperes, and an electromotive-force of 47·5 volts.

The curve of the shunt dynamo is curiously different from that of the series dynamo. It begins with a straight or nearly straight portion, which turns up in a curve, and eventually returns nearly horizontally to the axis of electromotive-force. The straight portion represents the unstable state when the shunt current is less than its true critical value. The critical external current, if it can be so called, is that current for which the shunt begins to act fully, and in Fig. 162 is about 30 amperes. From this point the shunt current acts with great power, and the electromotive-force here rises very rapidly. The slope of the line which constitutes the first portion of the characteristic represents the resistance which for the particular speed may be termed the critical resistance, and in this case is about 1 ohm. If the resistance of the external circuit becomes in the least degree altered, the electromotive-force and current will alter enormously. Any less resistance will cause the magnets to lose their magnetism at once. Any greater resistance will at once run the electromotive-force up above the critical value—in this case about 30 or 31 volts. If the resistance be steadily increased (and the slope of the line from O to the curve be increased in steepness) the electromotive-force will go on steadily augmenting, and become a maximum when the external resistance is infinite, that is to say when the circuit is completely opened and the shunt coils receive the whole of the electromotive-force of the armature. Fig. 163 depicts the characteristic of a shunt-wound Gramme dynamo capable of giving 400 amperes. In this case the curve e represents the external characteristic, from which the curve E is calculated by adding to the ordinates portions equal to $r_a\ i_a$. As the conductors of the armature could not safely carry more than 400 amperes, the dotted portion of the curve represents results not actually observed. It is instructive to contrast the characteristic of the shunt dynamo with that of the series dynamo (Fig. 153). In the series dynamo also, the first part of the characteristic is a sloping line, and the tangent of the angle of its slope is also the critical resistance for the given speed. But the series dynamo will only work if the resistance of the external circuit is *less* than the critical value, and the shunt dynamo will only work if the external resistance is *greater* than the critical value. The contrast is even better shown by drawing a couple of curves in the two cases—not characteristics—showing the relation between the potential at terminals and the resistances of the external circuit. Fig. 164 shows this for a series machine, and Fig. 165 for a shunt machine. The electromotive-force of the one drops suddenly when the resistance exceeds 2 ohms; that of the other rises suddenly when the resistance attains 1 ohm.

FIG. 163.



CHARACTERISTIC OF A SHUNT DYNAMO.

FIG. 164.

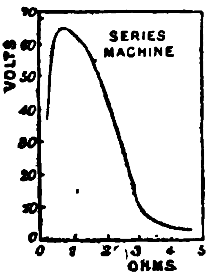
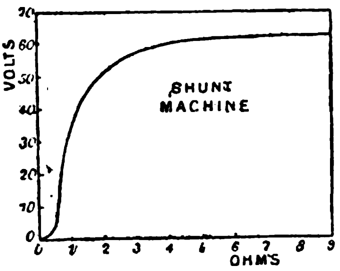
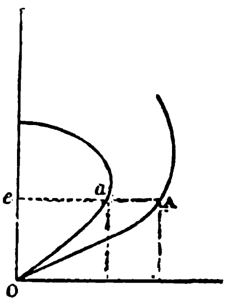


FIG. 165.



In the shunt dynamo the characteristic for a double speed cannot be obtained as in a series dynamo by doubling the height of the ordinates. For even if at a double speed we adjust the external resistances so that the external current is the same as before, we do not get a double electromotive-force because we do not get the same current as before round the shunt-magnet circuit. And if, on the other hand, we adjust resistances so that we get the same shunt current as before, and therefore a double electromotive-force, we do not get the same external current as before. If however we alter the external resistance, taking a larger current externally, so as to reduce the shunt current to its former value, the magnetization will remain as before. In that case the double speed will produce very nearly a double electromotive-force; but the shunt potential may remain as before, the external current being nearly double. This is shown in Fig. 166, where *e a* represents the external current in the first case, and *e* A the external current in the second. O A remains a straight line, but at this higher speed the slope is less. From this latter circumstance it may be foreseen that at higher speeds the resistance may be reduced to a lower value before the critical state is reached at which the machine "unbuilds" itself, *i. e.* discharges the magnetism from its field-magnets.

FIG. 166.



CURVE OF TOTAL CURRENT IN ARMATURE.

In the shunt dynamo the current in the armature is equal to the sum of the currents in the external circuit and in the shunt circuit; or

$$i_a = i + i_s.$$

A curve showing the relation between *i* and *e* is easily obtained. In Fig. 167 let the curve O *m i* be the "external characteristic" at the given speed. Take any point on it *m*; at that point the potential between terminals in volts is measured by the length of *m x* or O *e*, and the current in amperes is measured by the length O *x* or *e m*. Now draw the line *s* O at such an angle *s* O *x* that its tangent is equal to the resistance of the shunt. Then *e s* represents the current that will run through the shunt when the potential is O *e* volts. Add on to the end of *e m* a piece *m n* equal to *e s*; then the whole line *e n* represents the armature current i_a, when the potential has the value O *e*. A set of similar points may be found giving the new curve O *n* i_a required.

Fig. 167.

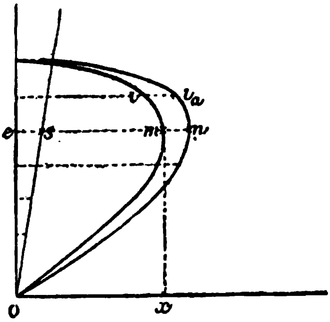
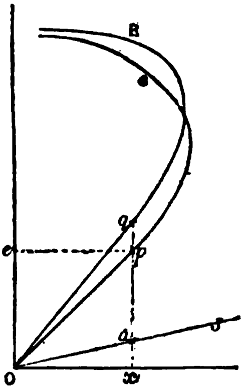


Fig. 168.



TOTAL CHARACTERISTIC OF SHUNT DYNAMO.

If the total electromotive-force E and the total current i_a be plotted out, we shall obtain the characteristic of the total electrical activity of the dynamo.

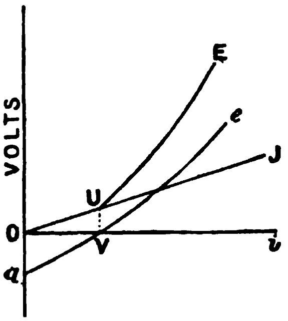
Draw, as in the preceding case, the curve for *e* and i_a. Let *p* be any point on the curve where the potential is *p x* or O *e* and the current *e p* or O *x*. Then draw a line O J at such an angle *a* O *x* that its tangent is equal to the resistance of the armature. Call the point where this cuts *p x*, *a*. Then *a x* represents the number of volts required to drive the current O *x* through the armature resistance. Add a piece *q p* equal to

$a\,x$ to the summit of the line $p\ x$. Then the height $q\,x$ represents the total electromotive-force E when the current i_a has the value represented by O x.

CHARACTERISTIC OF SHUNT DYNAMO, WITH PERMANENT MAGNETISM.

If there is residual magnetism in the field-magnets, there will be an electromotive-force induced, even before the shunt circuit is closed. In this case the characteristic would begin at a point p, a short distance along the horizontal axis. In fact the machine behaves as though there were already at work some small electromotive-force (not to be plotted), which had the effect of setting up already a current through the machine, so that the machine excites itself up with currents that are, in the early (and unstable) stages of the magnetization, proportional to the ampere-turns going round the shunt circuit, *plus* some imaginary ampere-turns causing the permanent magnetism. If there is on the field-magnet a second coil, by which an independent magnetization can be introduced, the same kind of result will follow: the characteristic will begin at some point, such as V, the electromotive-force due to the ampere-turns in the shunt being plotted out above O whilst the length O q below represents the part of the electromotive-force due to the ampere-turns (real or imaginary) of the independent magnetism; and O V represents the current which the machine will give when short circuited.

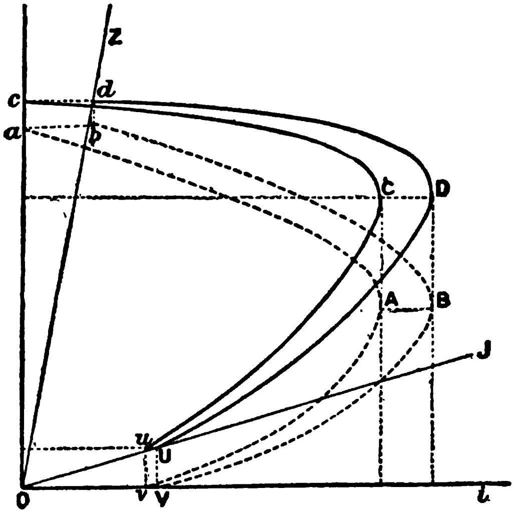
FIG. 169.



There will, in fact, be four curves for a shunt dynamo, namely, those in which the quantities plotted out are respectively e and i, e and i_a, E and i, E and i_a. Of these, the first is the *external characteristic*, and the fourth the *total characteristic.*

These four are depicted in Fig. 170, where they are named A, B, C, and D respectively. If D is given, A can be obtained in the following way:—Let the lines O J and O Z represent respectively by their slope the resistance of the armature and of the shunt circuit. Then curve B is got from D by deducting from the ordinates lengths equal to the portions of ordinates intercepted by the line O J, and curve C is got from curve D by deducting from the abscissæ lengths equal to the portion of the abscissæ intercepted by the line O Z. Then curve A is got by taking ordinates from B and abscissæ from C corresponding to any point on D.

Fig. 170.



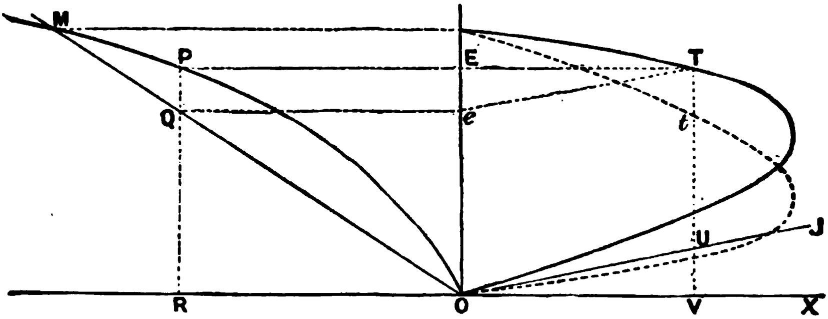
Four Curves of a Shunt Dynamo.

It may be noticed that whilst DB represents the lost volts due to internal resistance of armature, CD represents the lost amperes which go round the field-magnets. The lower the resistance of the armature, and the higher the resistance of the shunt, the less will these losses be. In fact, with a well-built modern machine the four curves lie very close together.

If the curve of magnetization of the machine is known it is easy to determine the characteristic by a geometrical construction. The curve of magnetization O P M will show the relation between N and the ampere-turns in the shunt coil, Z i_s in our notation.

Let this curve be set out to the left of the vertical axis, then the line O R may be divided out either in a scale representing ampere-turns or in a scale representing amperes, Z divisions of the former scale corresponding to one of the latter scale. The vertical scale plotted out along O E may in like manner represent either N or E; $n \, C \times 10^{-8}$ being the ratio of the readings of the scales. Now set out the line O M, making with O R an angle such that the tangent of its slope corresponds, in the units chosen, to the resistance of the shunt-winding; for example, if the shunt-resistance be 16, the line will pass through a point the ordinate of which represents 16 volts and the abscissa 1 ampere. Let this line meet the curve of magnetization at M. If we consider any point P on the curve, its ordinate P R will represent, according as we please, either the effective magnetism when the magnetizing current is O R, or the whole number of volts E induced in the armature; and the part of the ordinate Q R will represent the difference of potential *e*. Clearly then P Q will represent E – *e* that is to say, the volts lost in the armature, which are equal to $r_a \, i_a$. Now if on the right of the diagram we lay out a line O J at such an angle that the tangent of its slope represents the armature resistance r_a, then if V be taken so far along the horizontal axis that V U = P Q, the length O V will represent i_a. The most convenient construction is to project points P and Q across to E and *e*, and from *e* draw *e* T, parallel to O U, meeting E T in T; then drop a perpendicular from T giving the points *t*, U, and V, where T *t* = U V. T will be a point on the curve connecting E and i_a; *t* a point on the curve connecting *e* and i_a. From the latter curve the external characteristic can be got as shown on page 252. Of these hyperbolic curves the lower limb which returns towards O represents the unstable portion corresponding to the lower part of the magnetic curve. From the existence in the curves of a maximum value of i_a, where the curve turns round on the extreme right, it must not be inferred that the machine can yield this maximum current; on the contrary, the maximum current that the machine can safely give depends on the section of its armature wires, and these are—in the best machines—not intended to carry the current under such conditions. The working part of the curve is usually the top part (Fig. 171), and it will be obvious from the construction

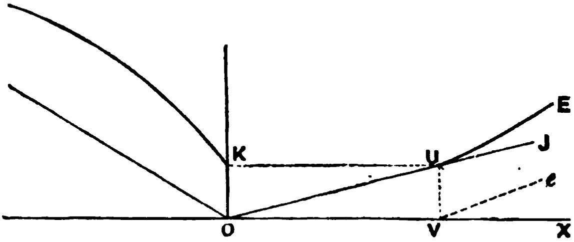
FIG. 171.



that the smaller the internal resistance, the farther will the curve extend to the right and the more nearly horizontal will the tops of both curves be; a good shunt dynamo, with very little internal resistance, being *nearly* self-regulating for constant potential.

If there be no initial or residual magnetization, the curves

FIG. 172.



will both pass through O; but neither of them will do so if there is initial or residual magnetization. In that case the curve of magnetization will commence above O at some point such as K, Fig. 172, and the lower ends of the two curves for

E and *e* will end at points so far to the right that the width U V = K O. With almost every shunt dynamo it is found that if descending values of *e* are taken (at any given speed) *e* becomes zero, whilst *i* has still a definite value.

It will also be noticed that the limiting value of E depends on the slope of M O, that is to say, on the resistance per turn of the shunt coil; any diminution of the resistance per turn will raise E by forcing up to a higher degree the magnetization corresponding to a given value of *e*.

CONTRAST BETWEEN SERIES DYNAMO AND SHUNT DYNAMO.

The difference between series dynamos and shunt dynamos in their behavior when the resistance of the current is increased or decreased, has already been touched upon in p. 263. In electric lighting, dynamos are usually required either (*a*) to supply glow-lamps arranged in parallel, in which case the dynamos must maintain a constant potential at the mains, or else (*b*) to supply arc-lamps arranged in series, in which case the dynamo is required to yield a constant current. In the case where the potential is to be constant, the current will vary with the number of lamps in parallel; in the second case, where the current is to be constant, the electromotive-force must vary as the number of lamps in series.

To understand the applicability of series or shunt dynamos to either of these tasks, it will be convenient to construct (either from experiment or from theory) comparative curves. In the case of parallel distribution, every additional lamp switched on across the mains adds to the conductance of the circuit an amount equal to its own conductance (*i. e.* equal to the reciprocal of its own resistance). It is therefore expedient to plot out together the values of *e* and of $\frac{1}{R}$. This has been done in Fig. 173 for two dynamos, for each of which the maximum value of *e* was the same. It will be seen that for neither a series nor for a shunt machine does the value of *e* remain constant as the number of lamps across the mains is increased. The shunt machine gives the more nearly constant potential, but falls off as the number of lamps is increased.

In the case of single-circuit distribution to lamps in series, every additional lamp adds to the resistance of the circuit, and in this case it is expedient to plot out together the values of *i* and R. Fig. 174 shows the result for the two kinds of machine. It will be seen that neither machine gives anything like a constant current; but for the shunt machine there is just one brief stage, namely, when its current is at the maximum, where the value is more constant than anything that the series dynamo can give. The dotted part of the curve corresponds to the case of a series dynamo so designed as to have a drooping characteristic (like Fig. 157, p. 256), which gives more nearly (with moderately small resistances) a constant current. But it is abundantly clear that something more than a simple series or simple shunt machine is requisite to give a real self-regulating machine for either purpose.

FIG. 173.

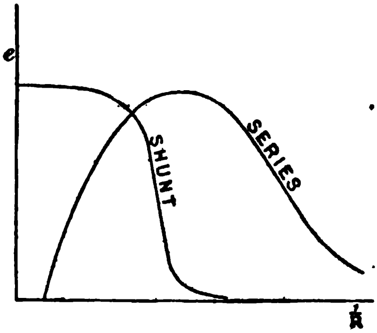
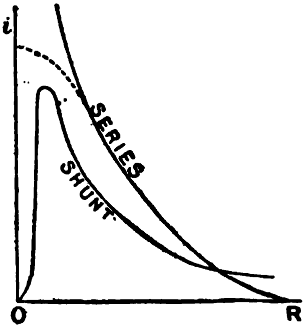


FIG. 174.



FURTHER USE OF CHARACTERISTICS.

The following examples of the further use of characteristics are taken from Dr. Hopkinson's paper in the *Proc. Inst. Mech. Engineers* for April, 1880 :—

To Determine Lowest Possible Speed of Dynamo running an Arc Lamp.

It appears that with the ordinary carbons, and at ordinary atmospheric pressure, no steady arc can exist with a less difference of potential than about 40 volts; and that in ordinary work, with an arc about ⅛ inch long, the difference of potential is from 45 to 50 volts. Assuming the former result about 40 volts for the difference of potential, the use of the curve of electromotive-forces may be illustrated by determining the lowest speed at which a given machine can run and yet be capable of producing a short arc. Taking O as the origin of co-ordinates (Fig. 175), set off upon the axis of ordinates the distance O A equal to 20 40 volts; draw A B to intersect at B the negative prolongation of the axis of abscissæ, so that the ratio $\frac{\text{O A}}{\text{O B}}$ may represent the necessary metallic resistance of the circuit. Through the point B thus obtained draw a tangent to the curve, touching it at C, and cutting O A in D. Then the speed of the machine, corresponding to the particular curve employed, must be diminished in the ratio $\frac{\text{O D}}{\text{O A}}$, in order that an exceedingly small arc may be just possible.

FIG. 175.

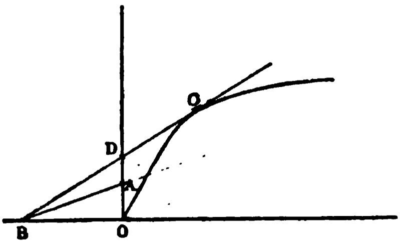
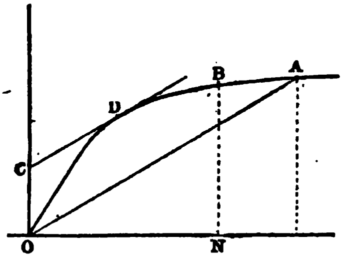


FIG. 176.



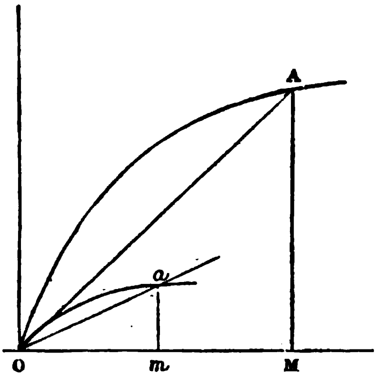
Use of Characteristic to Explain Instability of Arc Light.

The curve may also be employed to put into a somewhat different form the explanation given by Dr. Siemens at the Royal Society respecting the occasional instability of the electric light as produced by ordinary dynamo-electric machines. The operation of all ordinary regulators is to part the carbons when the current is greater than a certain amount and to close them when it is less; initially the carbons are in contact. Through the origin O (Fig. 176) draw the straight line O A, inclined at the angle representing the resistances of the circuit other than the arc, and meeting the curve at A. The abscissa of the point A represents the current which will pass if the lamp be prevented from operating. Let O N represent the current to which the lamp is adjusted; then if the abscissa of A be greater than O N, the carbons will part. Through N draw the ordinate B N meeting the curve in the point B; and parallel to O A draw a tangent C D, touching the curve at D. If the point B is to the right of D, or farther from the origin, the arc will persist; but if B is to the left of D, or nearer to the origin, the carbons will go on parting till the current suddenly fails and the light goes out. If B, although to the right of D, is very near to it, a very small reduction in the speed of the machine will suffice to extinguish the light.

Relation of Characteristic to Size of Machine.

Suppose that a certain dynamo of a given construction has for its characteristic the curve O *a* (Fig. 177). What will be the characteristic of a dynamo built of precisely the same type, but with all its linear dimensions doubled? The surfaces will be four times as great, the volume and weight eight times as great. There will be the same number of turns of wire, but the length will be doubled and the cross-section quadrupled, and therefore the internal resistances will be halved. If the resistances were adjusted so as to give the same current as before, the new machine would have only half the intensity of field of the small one. But if adjusted to give the same intensity of field as before, the current will be doubled.

FIG. 177.



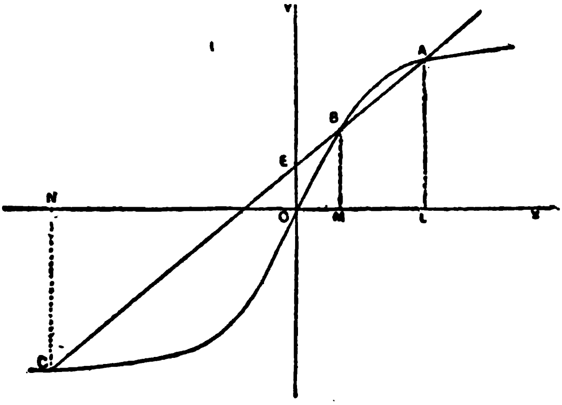
Now as the area of the rotating coils is increased fourfold, there will be four times as many lines of force cut (at the same speed), and therefore the electromotive-force will be four times as great. But we only wanted the current doubled. That is to say, the resistance will have to be doubled if the field is to be of the same intensity. To represent this state of things, take the point *a* on the characteristic of the small machine, and draw the ordinate *a m*. Draw O M, double O *m*, and at M erect an ordinate A M four times the length of *a m*. The new characteristic will pass through A. Also the resistance—the slope of O A—will be double that of O *a*. The points *a* and A are similar points with respect to the saturation of the iron of the magnets; and it is this which determines the practical limits to the economic working of a dynamo of given type at a given speed. Hence we see, with quadrupled electromotive-force and double current, the electric energy evolved per second will be eight times as great as with the smaller machine when worked up to an equal saturation limit. These points may be compared with the discussion of the relation of size to efficiency on p. 117.

Application of Characteristics to Dynamos used in Charging Accumulators.

The following problem is of great practical importance:—*Suppose a dynamo is used for charging an accumulator, and is driven at a given speed, what current will pass through it?*

Dr. Hopkinson has given a solution of this problem for the case of a series dynamo. Draw the total characteristic of the dynamo (Fig. 178) for the given speed. Along O Y set off O E to represent the electromotive-force of the accumulator, and through E draw the line C E A, making an angle with O X such that its tangent represents the resistance of the whole circuit, including the accumulators. This line will cut the characteristic in the points B and A; and, if the characteristic be repeated backwards, in C also. This negative branch of the characteristic is simply the characteristic of the dynamo when the current through it is reversed, and its electromotive-force therefore also inverted. Then O L represents the actual current in the circuit; O M represents an unstable current which might exist for a moment; and O N represents the current which would traverse the circuit were the accumulators to overpower the dynamo and reverse it, as indeed frequently happens when series dynamos are so used. For it will be observed that if, as is the case when accumulators are reaching their full charge, their electromotive-force were to rise, or the resistance of the circuit to increase in con-

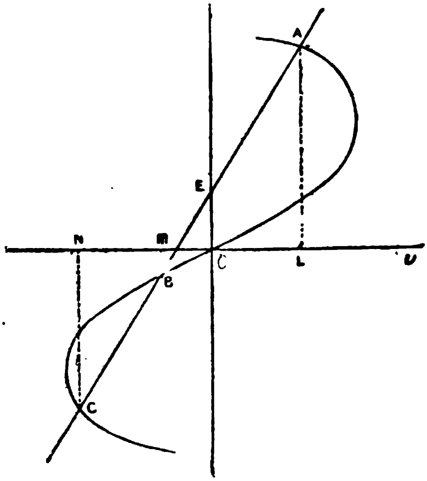
FIG. 178.



sequence of heating, the inevitable result would be to diminish A L, the effective electromotive-force, and to diminish the current O L, so that the magnetism of the field-magnets will also drop, and the point A will be brought nearer to the position of instability at the bow of the curve.

With the shunt dynamo the case is different. Let Fig. 179 represent the characteristic of the shunt dynamo, the external current being plotted along O X, and the total electromotive-force along O Y. Draw the line C E A as before. Then it cuts the positive branch at A, and O L is the current in the main circuit. If, now, either the counter electromotive-force of the accumulators or the resistance of the circuit increases, the effect will be to move the point A to a higher point on the curve. The charging current O L may diminish, but the shunt current will increase or the effective electromotive-force A L will be increased. Therefore with the shunt dynamo there will be no likelihood of the accumulators overpowering and reversing the dynamo.

FIG. 179.



CHAPTER XI.

CONSTANT POTENTIAL DYNAMOS.

Conditions of Supply.—The conditions of electric supply necessitate that the output of the dynamo should be regulated correspondingly. For some purposes—as for feeding a system of incandescent lamps in parallel—the current must be supplied to the mains at an absolutely *constant potential*, or, as some popularly phrase it, at a *constant pressure;* that is to say, the difference of potentials between the mains at the terminals of the dynamo, or at the lamps, must be constant. This, of course, implies that the current delivered by the machine shall vary exactly in a ratio inverse to that of the resistance of the external circuit, increasing, as the resistance is diminished, by adding to the number of lamps across the mains of the circuit. But we have seen that, owing to two causes —(1) internal resistance, (2) demagnetizing reactions of armature—the volts at the terminals at full load fall short of the value they would have (at the same speed and magnetization) at zero load. The *lost volts* increased with the load. Hence means must be taken to compensate for the lost volts if the supply is to be maintained *at a constant pressure.* If a dynamo is to supply lamps at, say 60 volts, the pressure must not be allowed to fall to 58 or 57 volts when all the lamps are at work.

For some other purposes, as for supplying a set of arc lamps connected in a simple series, or for charging a number of sets of accumulators in different houses, or for running a number of motors in different places on one line, it is necessary to maintain in the line an absolutely *constant current*, no matter how many or how few lamps or motors may be at work. This, of course, means that when the resistance of the main circuit is increased by the switching-in of more lamps, the dynamo must of itself put forth a proportionate increase of electromotive-force.

The two ends to be attained by regulation are therefore not only distinct, but incompatible with one another; a dynamo cannot possibly keep its electromotive-force constant, and at the same time vary it in proportion to the varying resistance of the external circuit. The two systems must therefore be kept absolutely apart. They are adapted to entirely different cases of electric distribution. Their theory is different; and the practical modes for carrying them out are different also.

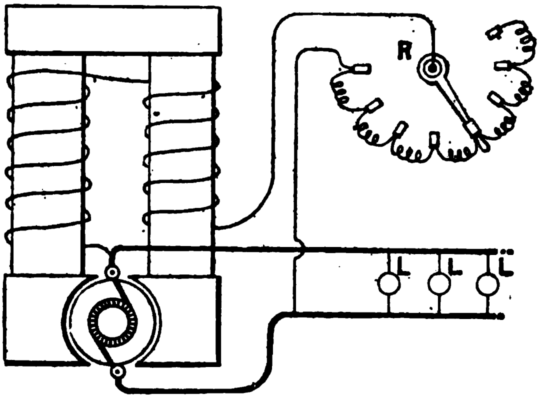
Constant-current machines, as required for arc-lighting, and for special glow lamps in series, are described in Chapter XVII. The present chapter will deal only with machines for supply at constant pressure.

There are various ways of governing dynamos so as to maintain either a constant potential or a constant current. Some of these methods involve hand regulation; others, automatic switching in or out of resistances, to vary the excitation of the field-magnets; others, automatic adjustment of the brushes; and others, electrical governing of the speed. The chapter on Regulators deals with these. Let it be noted in the first place that the voltage of a given dynamo depends, as shown by the fundamental equation (p. 47), on three things —the speed, the number of armature-windings, and the magnetic flux: hence it follows that any one of these might be used to control the output of the machine. The speed can be changed by purely mechanical contrivances. The number of effective armature conductors can be changed by shifting the brushes forward beyond the neutral point. The magnetic flux can be varied by altering the magnetizing force that excites the magnetism or by changing the disposition of the magnetic circuit. All these devices for governing dynamos have been used.

In cases of isolated plant it may be convenient to apply a governor (such as Willans's or Richardson's) to so vary the speed in accordance with the demands on the circuit as to maintain a constant electric pressure; but this is not satisfactory when the engine has other work than driving a single dynamo. Hence, methods have been preferred which admit of the maintenance of a constant speed of driving. Throughout this chapter this condition will be assumed to hold good; and as a purely magnetic method of regulation is but little used, we need only deal here with the methods that depend on the varying magnetizing forces. Some of these methods are adapted for hand-control, whilst others are automatic.

Edison's Regulator.—In Edison's method of supplying mains at a constant potential a shunt dynamo is employed, a variable resistance, or rheostat, R, being introduced into the shunt-circuit (Fig. 180). A lever moved by hand, whenever the potential rises or falls below its proper value, makes contact on a number of studs connected with a set of resistances, and thus controls the degree of excitation of the field-magnets. A similar device has been used in several other systems. To make the arrangement perfect the variable resistance should be automatically adjusted by an electro-magnet the coils of which are an independent shunt across the mains. Edison has indeed used such a device. The shunt dynamo, if well constructed, is, as shown on p. 270, nearly constant in its voltage; the pressure at the terminals falls off very little at full load. With such a dynamo, but a small

FIG. 180.



EDISON'S METHOD OF REGULATING.

increase of exciting power is needed to make up for the lost volts at full load. The regulating rheostat is equally applicable to a separately-excited machine.

Self-regulating Dynamos.—Seeing that an increase of magnetism is required to compensate for the lost volts, the dynamo may be made self-regulating if the increase of current in the main circuit, which causes the drop in the volts, can be made automatically to cause also a compensatory augmentation of the magnetism. If, in addition to the exciting coil which produces the requisite initial magnetization of the field-magnet, there is provided a compensating coil of wire thick enough to carry the main current, the desired end will be attained. If the machine is shunt-wound to begin with, and a compensating coil in series with the armature is thus added, the combination is usually termed a "compound" winding. The term "compound dynamo" having been introduced by Messrs. Crompton and Kapp to signify a dynamo with mixed series and shunt-winding, by analogy with the engineers' term "compound engine" for a steam-engine working with both high- and low-pressure cylinders. Compounding is not, however, the only mode of self-regulation; for a compensating series-coil is equally applicable to any well-designed continuous-current dynamo in which the initial magnetism is independently or constantly excited. The following combinations are possible:—

(*i.*) Series regulating coils + permanent magnets to excite the field initially, with an independent constant magnetization.

(*ii.*) Series regulating coils + an independent current circulating in separate coils round the field-magnets, to produce an independent constant magnetization.

(*iii.*) Series regulating coils + an independent current circulating in the main circuit (and generated either by a battery or by an independent magneto-dynamo) having the effect of partly exciting the field-magnets, with an independent constant magnetization.

(*iv.*) Series regulating coils + shunt-magnet coils supplied by a portion of the current of the machine itself thereby partly exciting the field-magnets, with an independent and nearly constant magnetization.

(*v.*) For alternate-current dynamos, coils in series with the main circuit cannot be used, but they may be compounded by providing them with regulating coils supplied with a current derived (by a suitable transformer) from the main-circuit currents, and proportional to them, the derived currents being first sent through a suitable commutator to rectify them. The independent magnetization may be derived either from an auxiliary exciter, or from a separate coil or group of coils in the armature, or, in fact, by another transformer, the primary of which is placed across the mains as a shunt, in either of the latter cases the current being properly commuted.

Theoretically, several other self-regulating combinations are possible; for example, a machine with a long armature lying between two separate field-magnets, one independently excited, the other in series; a series machine with unsaturated magnets combined with a (quasi-independent) series machine with over-saturated magnets on the same shaft; a series machine having two sets of field-magnet poles at different leads, one of the sets of poles being the series-excited set, the other excited independently, or in shunt circuit; &c.

THEORY OF SELF-REGULATION.

In considering the theory of self-regulation we shall proceed as follows:—First find an expression for the potential at the terminals of the dynamo. This will, in general, consist of three terms. Secondly, we shall consider these three terms as to whether their factors are constants or variables. Then, having ascertained which of the terms contain variable factors, we must consider what conditions must be laid down (such as prescribing a particular speed or a particular number of windings) in order that the terms containing variable factors shall disappear. These conditions will be embodied in an "equation of condition," which will be then discussed. In general it will be found that if the speed is prescribed beforehand, there will be a certain "critical" number of regulating coils to be deduced; or, on the other hand, if the number of regulating coils is prescribed beforehand, there will be a particular or "critical" speed at which self-regulation holds good.

It is possible to treat the theory either algebraically or geometrically. Both methods will be here used.

Case (i.). Series Regulating Coils + Permanent Magnets.—If the field-magnets are partly permanently magnetized, or if there are permanent steel magnets in addition to the electromagnets, giving a partial permanent field, independent of that due to the current in the circuit, we may denominate the number of magnetic lines in this independent field as $\mathbf{N}_1$.

Now the fundamental equation of the series dynamo is

$$E = n\, C\, \mathbf{N},$$

and the difference of potential between the terminals, otherwise called the pressure, is shown on p. 227 to be

$$e = E - (r_a + r_m)\, i.$$

But $\mathbf{N}$, the number of magnetic lines that pass through the armature at any instant, is made up of two parts, the permanent independent part $\mathbf{N}_1$, and a part depending upon the current i, and equal to

$$\frac{4\pi S i \div 10}{\Sigma \frac{l}{\mu A}};$$

where S is the number of turns in the regulating coil, l the length of the magnetic circuit, A its cross-section, and μ the *average* value of the permeability (see p. 318) between the two extreme values that it has when i is zero and when i is at its maximum. If for brevity we write

$$4\pi \Big/ \Sigma \frac{l}{\mu \mathrm{A}} \overset{\times 10}{=} q,$$

we may then write the variable part of $\mathbf{N}$ as q S i; and therefore,

$$\mathbf{N} = \mathbf{N}_1 + q \mathrm{S} i;$$

and we get, as the complete expression for e,

$$e = n \mathrm{C} (\mathbf{N}_1 + q \mathrm{S} i) - (r_a + r_m) i,$$

or

$$e = n \mathrm{C} \mathbf{N}_1 + n \mathrm{C} q \mathrm{S} i - (r_a + r_m) i.$$

The expression on the right-hand side of this equation consists of three terms, of which the first contains the speed and two constants as factors. The last two contain a variable, the current, and one of them also contains as factors the speed n and the number of regulating coils S. If S is prescribed beforehand, then the particular speed at which the dynamo is self-regulating will be clearly that speed at which the expression for e will contain nothing but constants. If n is prescribed beforehand, then we must vary S so as to eliminate the terms that contain the variable factor. Since the two last terms are of opposite sign, it is clear that by varying S or n, or both, the value of n C q S may be made numerically equal to $r_a + r_m$. Then at the constant speed, which we will call n_1, the last two terms will cancel one another out, or,

$$n_1 \mathrm{C} q \mathrm{S} i - (r_a + r_m) i = 0.$$

That is to say, S and n_1 must be such that

$$n_1 \mathrm{C} q \mathrm{S} = r_a + r_m. \qquad \text{[XIII.]}$$

This is the equation of condition.

If the condition laid down in this equation is observed, then the last two terms for e disappear, and we have simply,

$$e = n_1 \mathrm{C} \mathbf{N}_1 = \textit{a constant.}$$

Having thus proved that, at the given speed, e is a constant, it is worth while to enquire what it is that determines the value of e. Clearly e is directly proportional to $\mathbf{N}_1$, the independent and permanent field magnetism. Therefore, we can arrange that the dynamo, still driven at the given speed, shall give any potential we please, within limits, provided we alter $\mathbf{N}_1$ in the requisite proportion.

Suppose that the speed is prescribed by mechanical considerations, then the proper or critical number of regulating coils is given by the expression

$$S = \frac{r_a + r_m}{n C q}. \qquad \text{[XIV.]}$$

This is instructive. The higher the internal resistance of a dynamo the greater must be the number of the regulating coils in series, if it is to be self-regulating.

Returning to the equation of condition, we will write it in the second form—

$$n_1 C q S = r_a + r_m,$$

which gives us as the value of the critical speed,

$$n_1 = \frac{r_a + r_m}{S} \cdot \frac{1}{C q}.$$

This shows us that, if the series coils are prescribed there will be a certain critical speed of self-regulation, and this speed will be higher the greater the internal resistances are.

Lastly, we may write the last equation in the following way,

$$\text{critical speed} = \frac{\text{total internal resistance}}{\text{number of turns of series coils}} \times \text{a quantity}$$

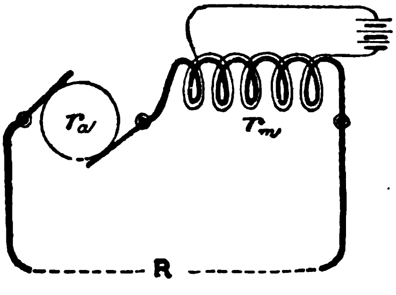
depending only on the armature windings and on the magnetic circuit and its working permeability within the range for which regulation is required.

So far we have assumed that the only cause of drop of pressure that needed to be compensated for was that due to internal resistances. But the drop of pressure due to the demagnetizing action of the armature is in modern machines a consideration of even more importance. To take account of this action we must remember that if the angle of lead λ is known, the demagnetizing belt of conductors (see p. 89) will be that comprised within an angle of 2 λ, namely $C\lambda / 90°$. And each such conductor carries $\frac{1}{2}\,i$ amperes, making the demagnetizing ampere-turns $C\lambda i \div 180°$. Or, if the number of conductors within the angle λ is called D, the demagnetizing ampere-turns will be $2\,D \times \frac{1}{2}\,i = D\,i$. This is for drum machines: for ring machines the product must be doubled. As however, these turns are situated over the armature, whilst the compensating coils are wound on the field-magnet, their action will be greater in proportion approximately to the leakage coefficient v (see p. 183). Hence we shall have to increase S, the series coils, from the value found above to the value

$$S = \frac{r_a + r_m}{n_1\,C\,q} + D\,v. \qquad \text{[XV.]}$$

Case (ii.). Series Dynamo + Separately-exciting Coils (see "*Series and Separate,*" Fig. 44, p. 58).—In this case there is an independent magnetism due to a current carried round the field-magnets in separate coils, and providing a part of the field magnetism. The connexions are shown in Fig. 181.

Fig. 181.



If we call the number of magnetic lines due to the independent excitation $\mathbf{N}_1$, the same argument holds good as in the preceding case, and the same conclusions. $\mathbf{N}_1$ will not, however, be really a constant, for the effect of the introduction of a constant amount of magnetizing force will vary with the degree of saturation resulting from the *whole* magnetizing force. If, however, the average working permeability throughout the range of regulation is taken into account in the calculation of N_1 as well as in that of S, then any falling-off in the effect of the independent exciting current is implicitly provided for.

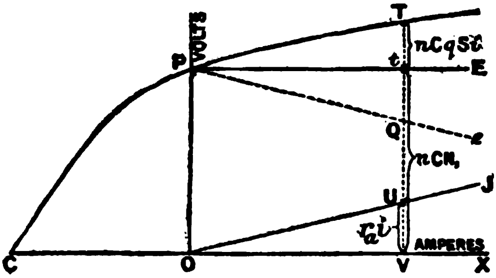
Messrs. Wright & Kapp have accomplished the same end as Case ii., using one coil only in the main circuit, to which coil, however, a battery, or the circuit of a separate dynamo, is applied as a shunt. M. Picard has made a somewhat similar suggestion.

Geometrical Demonstration of Cases (i.) and (ii.).

On p. 230 it was shown how the values of the potential at terminals fall off in magneto and separately-excited dynamos as the current increases, e always being less [1] than E by an amount equal to $r_a i$.

To represent the facts, let O X and O P be taken as the axes for plotting out amperes and volts, and let O P represent the electromotive-force ($E = n_1 C N_1$) due to the permanent or independent magnetism, as measured when no current is running through the armature. Now, assuming

FIG. 182.



that the armature reactions are small enough to be neglected, E will at constant speed remain the same with all currents, but e will drop. From O set off the line O J at an angle such that its tangent represents the internal resistance of the machine. Now consider the case when the current i has the particular value corresponding to the length OV. The height

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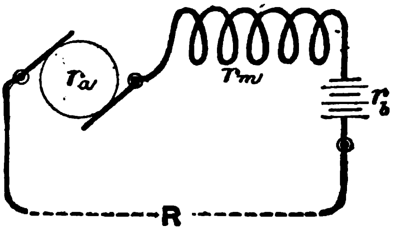
[1] This is illustrated in Fig. 150, p. 232, where the curve e shows the drop due to this cause, and the curve B the actual drop, due chiefly to this cause and partly to the demagnetizing reactions going on in the armature.

U V will be the drop in the external electromotive-force; for U V = tan U O V $\times$ O V = $r_a\, i$. Cut off from t V a portion, t Q = U V, and Q V will represent e. While the curve for E and i is approximately a horizontal line, the curve for e and i (the external characteristic) drops, as shown by the dotted line. Any point on the e curve can be got from the E curve by simply deducting from the height a piece equal to the corresponding width across the triangle J O X. Now it must be obvious that if when the E curve is horizontal the e curve slopes downward, we must use an E curve that slopes upward by a precisely equal amount, if we want to get a horizontal e curve; that is to say, if we want to get constant potential. How are we to get an upward sloping E curve? Remember that at a given speed, n_1, the value of E is n_1 C $\mathbf{N}_1$, where $\mathbf{N}_1$ means that the magnetic circuit has somehow (either permanently or by a separate current) been excited up to such a degree that $\mathbf{N}_1$ lines go through the armature. The same plotting that serves for volts will serve for values of $\mathbf{N}$ by choosing the appropriate scale; or, O P may represent $\mathbf{N}_1$. Therefore P is a point on a curve of magnetization, which will rise still higher if only we put on more ampere-turns of excitation. Therefore all that is required to be done is to put on the magnets a coil in series, having such a number of turns S that the ampere-turns S i will have the effect of raising the magnetism in the right proportion; in fact, so that T t shall be equal to U V. We have now got an E curve which slopes up—not quite a straight line, to be sure, but such that when we subtract the volts required to drive the current through the armature resistance, we get an e curve that is approximately level.

Comparing the algebraic and geometric methods, we see that t V corresponds to n_1 C $\mathbf{N}_1$; T t to n_1 C q S i; and U V to $r_a\, i$, or if the resistance of the added series coil is included in the slope of the line O J, U V will correspond to $(r_a + r_m)\, i$.

Case (iii.). Series Dynamo + Independent Electromotive-force thrown into the Main Circuit.—This really comprises two cases: where the independent constant electromotive-force is due to a battery, and where it is due to a separate magneto machine driven at a constant speed ("Series and Magneto," see p. 282). The argument is the same, however, for both cases. Fig. 183 will represent either case.

FIG. 183.



We have here as the whole electromotive-force of the combination E, the electromotive-force of the armature, plus E_b the independent electromotive-force thrown in from the battery or magneto machine. The difference of potential between the terminals, which we have always denominated as e, will be got by subtracting from $E_b + E$ that part of the electromotive-force which is devoted to sending current i through the internal resistances, which are now r_a, r_m, and r_b; so that we have

$$e = E_b + E - (r_a + r_m + r_b)\, i.$$

Now $E = n\, C\, q\, S\, i$; therefore, in order to make the last two terms cancel one another and leave e a constant, we must give the speed the value n_1 such that

$$n_1\, C\, q\, S = r_a + r_m\, r_b,$$

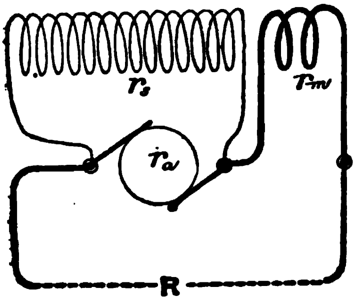
which is the equation of condition. In this case,

$$e = E_b.$$

This proves that in this case, too, the constant potential at the terminals is identical with that due to the independent excitation. Of course this does *not* mean that the dynamo does no work. On the contrary, it means this: that when the resistance of the external circuit is infinitely great, so that the dynamo does no work, then the only electromotive-force in the circuit is that due to the independent source.

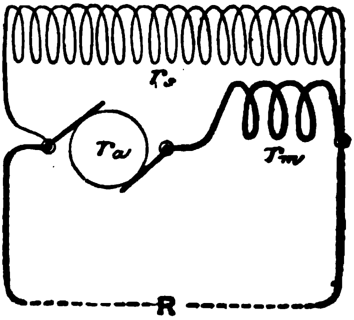
Case (iv.). Series Regulating Coils + Shunt Exciting Coils: "Compound Winding."—The compound-wound dynamo may be regarded as either a series dynamo to which some shunt windings have been added, so as to provide an initial magnetization, or as a shunt dynamo to which some series windings have been added to compensate for the drop of potential at the terminals. There are two possible methods of connecting the shunt coils to the dynamo, and the proportions differ slightly in the two cases. In the "short-shunt" method (see p. 60) the shunt coils are joined as a shunt to the armature part of the dynamo only, being connected across from brush to brush. In the "long-shunt" method the shunt coils are connected across the terminals of the machine, and may, therefore, be regarded either as a shunt to the external circuit, or as a shunt to the armature and series coils together. In the former arrangement the current through the shunt is not constant, because the potential at the brushes ϵ is not the e; and though e may remain fairly constant, ϵ does not, but increases when the external circuit's resistance decreases. In the latter arrangement the current through the shunt is constant if e is constant, and the case becomes one analogous to those already discussed, of an independent constant excitation. The connexions of the short-shunt methods are indicated in Fig. 184. Since in a well designed dynamo r_a is very small, r_m will also be very small, for few regulating coils in series are required. Moreover, as the shunt resistance r_s is

FIG. 184.



COMPOUND-WINDING : SHORT-SHUNT.

FIG. 185.



COMPOUND-WINDING : LONG-SHUNT.

relatively very great, the shunt current will be relatively small, and it makes very little difference therefore whether the shunt is connected across the brushes or across the terminals of the main circuit. The connexions of the long-shunt arrangement are as shown in Fig. 185.

The calculations for the two cases are practically identical, and involve the same kind of arguments. That for long-shunt is a little more simple, and is accordingly given.

We have then

$$E = n\,C\,\mathbf{N};$$
$$e = E - (r_a + r_m)\,i_a;$$

and as the magnetism depends on the total number of ampere-turns circulating around the field-magnet, we shall write,

$$\mathbf{N} = q\,(Z\,i_s + S\,i_a);$$

where q has the same signification as before (p. 283), namely,

$$= \frac{4\,\pi}{10} \Big/ \Sigma\,\frac{l}{\mu\,A};$$

or more strictly is the variable number representing, at the various stages of magnetization, the numerical ratio between $\mathbf{N}$ and the total number of ampere-turns for the magnetic circuit of the particular dynamo. It is of course best obtained by reference to such a diagram as Fig. 105. For the present purpose it is necessary to consider (1) the value which q has when the external current is zero, and when the only excitation is that due to the shunt, namely $Z\,i_s$ ampere-turns; this may be called q_o; and (2) the value which q has when the current in the armature is at the maximum for which the dynamo is intended to be used. If the maximum current is called x, this value may be called q_x. Then, as the current varies from o to x, the corresponding values of $\mathbf{N}$ will vary from

$$\mathbf{N}_o = q_o\,Z\,i_s$$

to

$$\mathbf{N}_x = q_x\,(Z\,i_s + S\,x).$$

Now between these two limits, which we may call the range for which the dynamo is required to be made self-regulating, q will have intermediate values, and one of these must be selected for use in the formula. The value $\frac{1}{2}(q_o + q_x)$ will not be far from a fair average. Let this average value be denominated q_1 in the equations which follow. Then from the three preceding equations we have

$$e = n\,\mathrm{C}\,q_1\,\mathrm{Z}\,i_s + n\,\mathrm{C}\,q_1\,\mathrm{S}\,i_a - (r_a + r_m)\,i_a\,.$$

Now here we have three terms, the first containing, as factors, the speed (which may be kept constant), and the shunt current i_s which will be made constant if e can be made constant: the second contains the speed also as a factor; the second and third both contain the variable current i_a. The two variable terms are of opposite sign. Now e cannot possibly be a constant, when two of its terms contain a variable as factor, unless the coefficients of that variable factor are such that they make those two terms cancel one another; e cannot be constant unless either the speed n or the windings S, or both, are so adjusted as to fulfil this. But these can be adjusted and even with a given value of S a particular value of the speed n_1 can be found, such that

$$n_1\,\mathrm{C}\,q_1\,\mathrm{S} = r_a + r_m\,. \qquad \text{[XVI.]}$$

This is then one of the two equations of condition; and then if the speed be given, the critical number of series-turns will be

$$\mathrm{S} = \frac{r_a + r_m}{n_1}\cdot\frac{1}{\mathrm{C}q_1}\,.$$

Or, if S is prescribed, the critical speed will be

$$n_1 = \frac{r_a + r_m}{\mathrm{S}}\cdot\frac{1}{\mathrm{C}q_1}\,.$$

If this condition be observed, then e will be constant and have the value

$$e = n_1\,\mathrm{C}\,q_1\,\mathrm{Z}\,i_s\,.$$

But this would leave e indeterminate. But we may reflect that though this equation might not give us the value of e, there will nevertheless be a determinate value for it, namely, the same value that e would have when there is no current taken from the dynamo at all, but when it is running on open circuit only. Under these conditions the value of e will be

$$e = n_1 \, \mathrm{C} \, \mathrm{N}_o - (r_a + r_m) \, i_s ;$$

or, since here q has the value q_o,

$$e = n_1 \, \mathrm{C} \, q_o \, \mathrm{Z} \, i_s.$$

But $e = r_s \, i_s$, whence we get

$$n_1 = \frac{r_s}{\mathrm{Z}} \cdot \frac{1}{\mathrm{C} \, q_o}. \qquad \text{[XVII.]}$$

Comparing this value of n_1 with that obtained in the first equation of condition, we get

$$\frac{r_s}{\mathrm{Z} \, q_o} = \frac{r_a + r_m}{\mathrm{S} \, q_1};$$

whence, finally, as the *second* equation of condition,

$$\frac{\mathrm{Z}}{\mathrm{S}} = \frac{r_s}{r_a + r_m} \cdot \frac{q_1}{q_o}. \qquad \text{[XVIII.]}$$

As q_o is proportional to μ_o the permeability when there is no external current, and q_1 proportional to the average permeability μ_1 for the range of working between zero current and maximum current, it follows that if there were no alteration of saturation, $q_1 \div q_o$ would equal 1. In the former editions of this work, wherein the theory of compounding was expressly based upon the supposition that there was no saturation—or in other words, that the permeability was constant—the formulæ obtained were admittedly incorrect for this reason. Dr. Frölich found for a certain Siemens series and shunt dynamo,

$$\frac{\mathrm{Z}}{\mathrm{S}} = 17 \cdot 7, \text{ whereas } \frac{r_s + r_a}{r_a + r_m} = 61 \cdot 9.$$

From which it is clear that μ_o must have been about 3·5 times as great as μ_1; in other words, this machine had an insufficient quantity of iron in its magnets or armature core, or in both.

This dynamo must have been both badly designed and of low efficiency; r_s ought to have been not 61·9, but at least 300 times as great as $r_a + r_m$. It will be noticed that, apart from the demagnetizing action of the armature, the amount of excitation to be provided for by the series coils is always proportional to the resistances that are in the main circuit and *internal to the points for which the constant difference of potential is desired;* this renders it possible in a case where the mains leading from the dynamo to the lamps are long so to compound the dynamo by adding more coils in series as to give a constant potential, not at its terminals, but at the distant point of the circuit where the lamps are to be used. This is a most valuable circumstance in all cases where the lamps are far from the dynamo, as in the lighting of mines from machinery at the surface; for then by *over-compounding*, one can obtain a constant pressure, not at the terminals of the dynamo, but on the mains at some point in the midst of the lamp-network. There is another advantage in over-compounding, namely, that when the full load comes upon a machine, the engine, however carefully governed, generally slows down a little, tending to produce a further drop in the voltage.

To compensate for the demagnetizing action of the armature, additional turns are required in the series coil, as explained above on p. 284. To make the last set of formulæ complete S should be replaced by S — D *v*.

ARRANGEMENTS OF COMPOUND WINDING.

Compound windings may be arranged in several different ways. If wound on the same core the shunt coils are sometimes wound outside the series coils: less frequently the series coils are outside the shunt. In some of Siemens' dynamos they are wound on separate frames and slipped on side by side over the same core. In other cases, where (as in Siemens' usual patterns) the pole is at the middle of the magnet core, one end of the core may carry the shunt coils, the other the series; or both the coils on one of the cores may be series coils, and both those on the other, shunt coils. In Elihu Thomson's machines the series coils are wound on frames close over the armature. In some of Siemens' machines with double magnetic circuits, the series coils were wound only on the cores adjoining that horn of the pole-piece which would otherwise be weakened by the reaction of the armature; with the effect that the distortion of the field was partly corrected. It is advisable to keep down the resistance of the series coils, as they will form part of the main circuit; whilst the additional resistance necessitated by winding the wire in coils of larger diameter is not altogether a disadvantage in a shunt coil. In the former editions of this work the recommendation was made to wind the series coils nearer the pole than the shunt coils. With the better magnetic circuits now employed in dynamos, this advice has ceased to have any weight. If the magnetic circuit through the ironwork be good, the position of the coils makes little difference.

PRACTICAL PROCESS FOR COMPOUNDING.

It is clear from the foregoing paragraphs that the compound machine, when run on open circuit, with only the shunt-current flowing, must give the same potentials at its terminals as it is to give as a compound machine. Hence this leads to the following practical process for compounding. Let the armature of the machine be run at the proper speed dictated by mechanical considerations, and let a voltmeter be applied at the terminals. Two experiments are then necessary. First, by means of temporary coils, having a known number of turns wound on the field-magnets, and furnished with measured currents from some accumulators or another dynamo, ascertain the number of ampere-turns that will suffice to excite up the magnets to this point. From this Z can be determined; for it is known beforehand that r_s must be at least 300 or 400 times (or sometimes as much as 1000 times) r_a; and therefore i_s is really known beforehand. Secondly, put into the main circuit some resistance to represent the maximum load of lamps, and while the machine is running at its proper speed, ascertain, using still the temporary coil and accumulators, how many ampere-turns of excitation are needed in total when the machine is doing full work, subtracting from this the value of $Z\, i_s$ obtained in the first experiment, the remainder gives the number of ampere-turns which the series coil must furnish, and as the maximum current is known, S can at once be calculated. The same process suits for *over-compounding*, the excitation at full load being raised until the volts at terminals rise to the higher number of volts that will allow for the drop in the leads.

DESIGN OF CONSTANT POTENTIAL MACHINES.

It is obviously of importance in such machines that the iron parts should be so designed that (1) the characteristic should be as nearly straight as possible in that portion of it corresponding to the working range of currents for which regulation is desired; (2) that it should not turn down. Consequently it is of importance in such machines that there should be just so much iron in the magnetic circuit that the current due to the shunt should carry the initial magnetization over the knee of the curve of magnetization; and that the reactions due to the armature currents should be small; or in other words that there must not be too much copper on the armature, and that the field-magnets should be relatively powerful. Also, of course, the resistance of the armature should be kept as small as possible.

TIME REQUIRED FOR COMPOUNDING.

Machines which have very solid field-magnets cannot suddenly respond by a change in magnetism to a sudden change in the demand for current, in consequence of the currents induced in the solid iron which oppose and delay changes in its magnetic state. Hence, such machines, even though compound-wound, fail to keep the pressure constant, as they cannot act quickly enough. For such work as supplying current to an electric tramway, an over-compounded dynamo with *laminated* field-magnets is the best generator.

CHARACTERISTIC OF COMPOUND DYNAMO.

In the original theory of constant potential machines devised by Marcel Deprez, the argument was based upon the absence of saturation, and the presence of an initial independent magnetization. The following was the argument of Deprez. If there is a permanent excitement of magnetism quite independent of that due to the main-circuit coils of the dynamo, the characteristic (Fig. 186) will not start from O, but from some point above it depending on the amount of independent magnetization and on the speed. Let the starting point be P. O P is the electromotive-force between terminals when the main circuit is open, but there is no external current until the circuit is closed, and then the characteristic rises in the usual fashion from P to Q. Draw O J at the proper slope to represent the resistance of the armature and series coils together. Now consider a line O E drawn at such an angle that the tangent of its slope represents the total resistance of the circuit at any particular moment. Then E x is the total electromotive-force at that moment, and a part of this, equal to $a\,x$, will be employed in driving the current O x through the resistance of armature and series coils. The remaining part E a represents the difference of potentials between the terminals of the external circuit. So the problem resolves itself into this: how to arrange matters so that E a shall always be of the same length as O P, no matter how much or how little the line O E may slope. Clearly the only way to do this is so to arrange the speed of the dynamo that the part from P to Q shall be parallel to O J. If the speed is reduced exactly to the right amount the inclination of the characteristic will be equal to that of the line O J. Then, as shown in Fig. 187, the potential between the terminals will be constant. It will be seen that this agrees with the deductions arrived at in the algebraic treatment of the question: namely, that the critical speed is proportional to the internal resistance; and that the constant difference of potential E a is equal to that due to the independent magnetization O P at the critical speed.

It should also be noticed that if the part of the characteristic be not straight, that is to say, if the field-magnet cores are becoming saturated, the regulation cannot be perfect. If the line P Q be curved, then the potential for large currents will not be equal to that for small currents. If, in the practical process for winding the magnets, the coils have been wound so as to make *e* the requisite number of volts, both on open circuit (*i. e.* at O P), and at another point (say at Q J), when the dynamo is feeding its maximum load, then there will in general be a slightly greater potential for intermediate loads, owing to the slight convexity of the curve between P and Q.

Fig. 186.

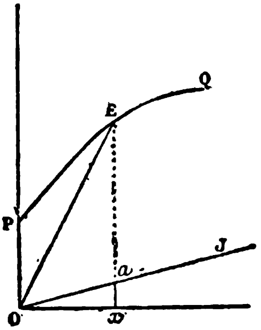
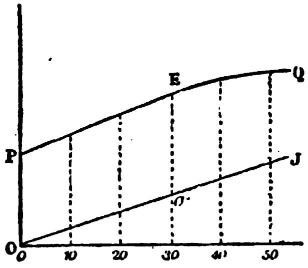


Fig. 187.



The above argument holds good whether the independent excitation be due to permanent magnetism or to a combination with separately-exciting coils (see pp. 58 and 59), or to shunt-exciting coils. In the latter case O P represents the potential at terminals due to shunt excitation alone.

The case of the "compound" dynamo is worth looking at from another point of view also. On p. 264 two curves—not characteristics—are given, showing the relation of electromotive-force to external resistance in a series machine and in a shunt machine. One begins at a certain height and falls when the resistance has attained a certain value; the other begins low and rises when the resistance has attained a certain value. It is conceivable that if a dynamo were wound with both shunt and series coils, so that each worked up to the same potential at the same speed, and so proportioned that the number of ohms at which one fell should be the same as that at which the other rose, then the compound machine

FIG. 188.

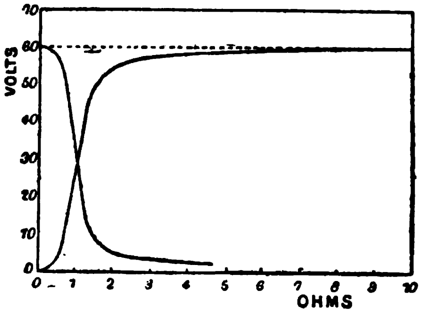
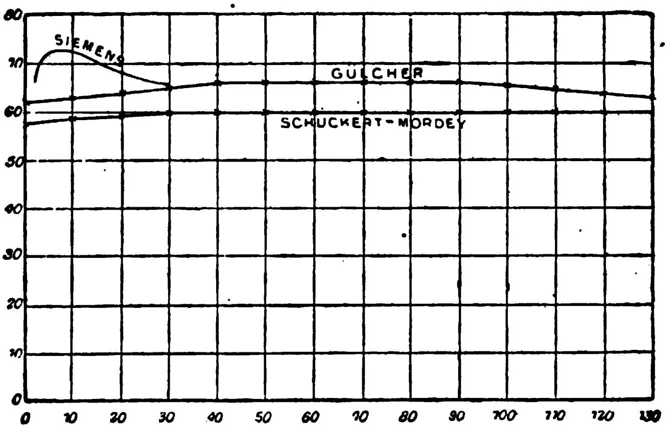


FIG. 189.



EXTERNAL CHARACTERISTICS OF COMPOUND-WOUND DYNAMOS.

should, as indicated in Fig. 188, give as a result of the double-winding, a constant potential. It remains to be seen how far this is attained in practice.

EXTERNAL CHARACTERISTICS OF SELF-REGULATING DYNAMOS.

Simultaneous observations of the external current *i* and the external potential *e* enable us to plot the external characteristic; which in a perfectly self-regulating dynamo would be a horizontal line. The curves given in Fig. 189 relate to an old Siemens dynamo,[1] a Mordey "Victoria" dynamo[2] (see p. 498), and a Gülcher machine (see p. 503).

If the number of regulating coils in series is too small, the characteristic will fall as the current rises; if too large, will rise slightly from the beginning near the origin (see Fig. 189). This latter case, however, is not always a disadvantage, for with machines worked singly on an engine the speed often falls in consequence of imperfect governing as the load on the dynamo is increased.

Esson's Observations.—Some observations by Mr. W. B. Esson, in the *Electrician* of June 1885, are worthy of consideration in connexion with recent theory. Mr. Esson asks why is it that compound dynamos wound so as to be self-regulating for a given speed, regulate fairly well at any speed within considerably wide limits? To explain this peculiarity he observes that in no dynamo is the quantity or quality of the iron such that the saturation effect can be neglected. If the magnetism were strictly proportional to the ampere-turns of excitation, there would be literally a critical speed. The approximate rule $\frac{S}{Z}=\frac{r_a+r_m}{r_s}$, gives the number of series coils much too low, for when the shunt coil has already excited a certain degree of magnetization, the series coil cannot produce its proportionate increase. In a series machine (designed to give a current of 20 amperes), the electromotive-force added to the machine by increasing the exciting current from 5 to 10 amperes is much greater than the electromotive-force added by increasing the current from 10 to 15 amperes. Again, a 100-volt machine (self-regulating), in which therefore the shunt gave excitement enough for 100 volts on open circuit, had series coils upon it which were able, when the shunt was removed and the full current on, to give 60 volts between terminals. The value of the series coil to excite magnetism is diminished as the excitation due to the shunt is increased. All this is, of course, due to the diminution in permeability of the iron of the machine as the degree of saturation increases. From this it follows that a certain relation must subsist between the speed of the machine and the degree to which the magnets are excited by the shunt coil. But the magnetism furnished by the shunt coil also depends on the speed, and increases with it. If, therefore, at one speed this relation is such as to produce self-regulation, the relation will be almost equally true at other speeds. At the high speed the relative value of the series coils is less, and at the low speeds it is greater; but the sum of the two effects may be constant. At speeds lower than the normal speed, the potential is lower when there is a large resistance in circuit than where there is a small resistance in circuit. At speed higher than the normal, the potential falls as the resistance is diminished. Mr. Esson deduces from the foregoing considerations certain practical hints as to how to improve the regulation of a dynamo whose potential rises either when many or when few lamps are in circuit.

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[1] See Richter in *Elektrotechnische Zeitschrift*, April 1883.

[2] See *Journal Soc. of Arts*, March 7, 1884.

Engineers desiring further information on compound winding of dynamos, are referred to a series of articles in the *Electrician*, in 1883, by Mr. Gisbert Kapp; also to two articles by Mr. Esson in the *Electrician* of June, 1885. Articles by M. Hospitalier in *L'Electricien*, and by Herr Uppenborn in the *Centralblatt für Elektrotechnik*, should also be consulted: and the student should above all read the series of papers published by Dr. Frölich in the *Elektrotechnische Zeitschrift* for 1885, and a still more remarkable paper by Professor Rücker in the *Philosophical Magazine* of June, 1885. Some account of these was given in the Appendices of the third edition of this book. The latest contributions to this question are by C. Zickler, *Centralblatt für Elektrotechnik*, ix. 264, 1887, and M. Baumgardt, *ib*. x. 281, 1888; and by Dr. Louis Bell in the *Electrical World*, xvi. 383, 1891.

CHAPTER XII.

ON WINDING OF ARMATURES. THEORY OF CONNEXIONS.

THIS Chapter is devoted to the theory of the ways of joining up and combining the conductors on the armatures of dynamos. Workshop details concerning materials and modes of construction are considered in Chapter XIII. At present we deal with the important preliminary considerations which apply to design rather than to construction.

It has been pointed out, on p. 41, that excepting for arc-lighting-machines, which usually have "open-coil" armatures, continuous-current dynamos are provided with closed-coil armatures, that is to say armatures on which, whether wound according to the ring, drum, or disk type, the winding is re-entrant on itself, the current dividing between at least two paths and reuniting as it leaves the armature. For machines with two poles there are but two such paths, the current dividing once only. But for multipolar machines there may be either two, or more than two, such paths; with one, or more than one, bifurcation of the current. The electromotive-force of the machine will obviously depend on the mode of connexion of the conductors, as to how many active conductors are connected in series. Hence the necessity of understanding the theory of armature winding.

To connect up rightly the conductors on an armature so as to produce the desired result is a simple matter in the case of ring winding, for continuous-current machines, whether of bipolar or multipolar type. It is a much less easy matter in the case of drum windings, especially for multipolar machines. Often there are several alternative ways of arriving at the same result; and the fact that methods which are electrically equivalent may be geometrically and mechanically different makes it desirable to have a systematic method of treating the subject.

In Chapter III., pp. 41 to 45, we have already considered the elementary structure of ring, drum, and disk armatures. Those elements would suffice for the consideration of small armatures coiled with only a few turns of wire. But when we proceed to the design of large machines, or of machines which are to be wound so as to give potentials as high as 400 or more volts, further information is needed. For example, suppose we have designed a 4-pole machine having a bar-armature with 100 bars spaced around its periphery, all in one layer, numbered consecutively from 1 to 100, and we desire to complete the end-connexions; we must be able to instruct the workman as to the order in which they are to be connected. Is he to connect the front[1] end of bar No. 1 right across to bar No. 50, or No. 49? Or is he to connect it across a quarter of the periphery, and, if so, is it to join No. 25 or No. 24, or to No. 75 or No. 76? To which return bar is he to connect the back end of the bar? And which bars are to be connected down to the commutator?

The object of the present Chapter is to give information on these points. Brevity is essential; and much more might have been written. Those who wish to go further should consult the writings of Hering,[2] Arnoux,[3] Fritsche,[4] Weymouth,[5] and Arnold,[6] as well as sundry patent specifications to which reference will be made.

As remarked above, there is generally little trouble in understanding a ring winding, provided the distinction between a right-handed and a left-handed winding is comprehended. So leaving for the present a further discussion of multipolar ring windings, we pass on to consider drum winding.

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[1] "Front" end means the end where the commutator is; armatures being always most conveniently regarded from this end.

[2] Hering: *Principles of Dynamo-Electric Machines*, New York, 1891.

[3] Arnoux: *l'Electricien*, xii. 1888, pp. 737, 774, 827.

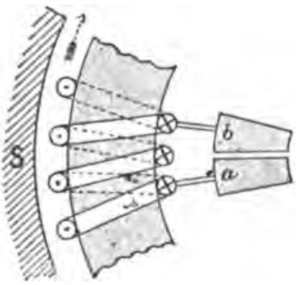
[4] Fritsche: *die Gleichstrom-Dynamomaschine*, Berlin, 1889.

[5] Weymouth: *The Electrician*, xxv. Nov. 7 to Dec. 19, 1890.

[6] Arnold: *die Ankerwickelung der Dynamomaschinen*, Berlin, 1891.

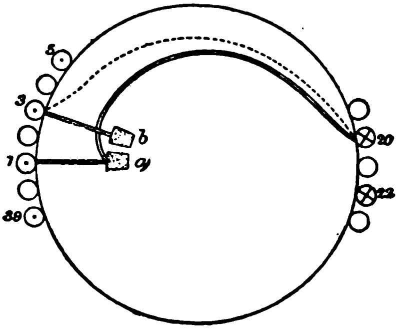
The first point to settle is what constitutes the difference between a right-handed and a left-handed winding. In the case of ring armatures there is no doubt. Fig. 190 shows one section of a ring, the direction of the currents being indicated in the same way as on p. 77, Figs. 61 to 63. As we pass right-handedly around the circle from *a* to *b* we follow a right-handed spiral path, the current climbing (as explained on p. 64) to the positive brush at the top. (A left-handed coiling, such as Fig. 31, p. 39, would give the positive brush at the bottom, unless either the rotation or the polarity of the dynamo were reversed.) Now consider Fig. 191, which depicts one element or section of a drum-winding having 40 external conductors. Starting from *a* to climb to *b*, and noting the direction of the currents in the conductors, it is obvious that *a* must be connected by a spiral connector across the front end of the drum to one of the descending conductors such as No. 20, from which at the back end another connector must join it to one of the ascending conductors, such as No. 3, where it is led to *b*, thus making one right-handed turn. Now examine Fig. 206, p. 318, Fig. 208, p. 319, and Fig. 212, p. 322. They are all left-handed, the last having eight turns of wire in one section. Note in passing that if the back connector in Fig. 191 from No. 20 to No. 3 had passed under the shaft, instead of over it, the winding would still have been a right-handed winding.

FIG. 190.



RIGHT-HANDED RING WINDING.

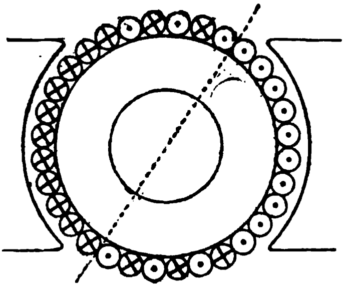
FIG. 191.



RIGHT-HANDED DRUM WINDING.

The next point is to ascertain over how many conductors these spiral connectors ought to pass. We connected No. 1 (*vià* the bar *a*) to No. 20, and then back to No. 3. Is there any reason why No. 20 should have been chosen and not No. 21, or No. 19, or No. 18? To understand this we must consider the question of commutation in the conductors as a whole, and also remember that there are two paths through the windings from brush to brush. This is a drum with 40 conductors in one layer: and there will be 20 bars in the commutator. Remember that the induced electromotive-forces will be directed from back to front in the conductors rising on the left, and from front to back in those descending on the right. It is natural to think that each conductor ought to be joined to the one that lies diametrically opposite to it. In that case No. 1 should be joined to No. 21, No. 2 to No. 22, and so forth. But this will not do. Each conductor on one side needs a return conductor on the other side. The even numbers may be looked upon as the returns for the odd numbers. Hence No. 1 ought not to be joined to No. 21. Shall it be joined to No. 20 or to No. 22? or shall we join it to No. 18? Nos. 20 and 22 lie on either side of the one that is diametrically opposite, and electrically it makes no difference which we select of these two. If we are going to use a back connector which returns over the shaft (as in Fig. 191), there is a slight saving of copper if we select No. 20. If the back connector returns under the shaft, either may be taken. More copper will be saved if we select No. 18 and return over the shaft, as the spiral connectors will be shorter. But if we thus connect across a short chord of the circumference, instead of taking the chord nearest to the diameter, we risk getting counter electromotive-forces in the turns that are in series from brush to brush. On the other hand, as Swinburne has shown, connecting across a short chord has the advantage that the armature has a less powerful demagnetizing action. The effect of winding across a chord subtending the span of the pole-piece is shown by Fig. 192, in which it will be seen the belt of demagnetizing conductors between the pole tips is now replaced by a belt, in which the currents flow in two opposing directions, thus neutralizing one another. In no case should the chord subtend a less angle than that subtended by the polar face. The rule then for connecting is as follows for a simple 2-pole drum armature. The number of conductors C being an even number, the front connector must cross from any conductor to that which is ½ C ± 1 further on (or ½ C ± 3 for shortening the chord); and the back connector must lead back to the next conductor but one. In the following winding table the letters F and B stand for *front* and *back*, and the letters U and D stand for *up* and *down*, meaning toward the front end, and from the front end respectively. From this it will be seen that starting with conductor No. 1, we follow *down* it to the back, there connect it to No. 22, then come *up* to the *front*, then come (connecting to a bar of the commutator in passing) to No. 3, go down this, and connect across the back to No. 24, and so on. The overlap is in all cases 21. At last we come to No. 20, up which we return to the front and connect (*viâ* the last bar of the commutator) to No. 1.

FIG. 192.



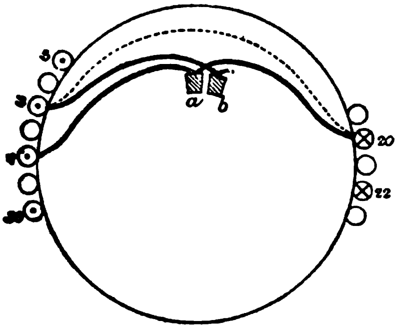
EFFECT OF CHORD WINDING.

WINDING TABLE. 2-POLE DRUM. 40 CONDUCTORS.

<table>
<tr><td>F</td><td colspan="2">B</td><td colspan="2">F</td><td colspan="2">B</td><td colspan="2">F</td><td colspan="2">B</td><td colspan="2">F</td><td colspan="2">B</td><td colspan="2">F</td><td>&nbsp;</td></tr>
<tr><td></td><td colspan="2">D</td><td colspan="2">U</td><td colspan="2">D</td><td colspan="2">U</td><td colspan="2">D</td><td colspan="2">U</td><td colspan="2">D</td><td colspan="2">U</td><td></td></tr>
<tr><td></td><td colspan="2">1</td><td colspan="2">22</td><td colspan="2">3</td><td colspan="2">24</td><td colspan="2">5</td><td colspan="2">26</td><td colspan="2">7</td><td colspan="2">28</td><td></td></tr>
<tr><td></td><td colspan="2">9</td><td colspan="2">30</td><td colspan="2">11</td><td colspan="2">32</td><td colspan="2">13</td><td colspan="2">34</td><td colspan="2">15</td><td colspan="2">36</td><td></td></tr>
<tr><td></td><td colspan="2">17</td><td colspan="2">38</td><td colspan="2">19</td><td colspan="2">40</td><td colspan="2">21</td><td colspan="2">2</td><td colspan="2">23</td><td colspan="2">4</td><td></td></tr>
<tr><td></td><td colspan="2">25</td><td colspan="2">6</td><td colspan="2">27</td><td colspan="2">8</td><td colspan="2">29</td><td colspan="2">10</td><td colspan="2">31</td><td colspan="2">12</td><td></td></tr>
<tr><td></td><td colspan="2">33</td><td colspan="2">14</td><td colspan="2">35</td><td colspan="2">16</td><td colspan="2">37</td><td colspan="2">18</td><td colspan="2">39</td><td colspan="2">20</td><td></td></tr>
</table>

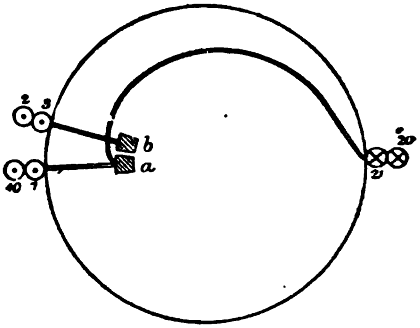
Simple as the matter may seem, the problem how to connect across the end of the drum from one conductor to that which is next but one, or next but three, to the diametrically opposite conductor, is not altogether easy when the mechanical and electrical difficulties are taken into account. To shorten the length of the long spiral connectors, and make the end connectors more symmetrical, the arrangement indicated in Fig. 193 is sometimes used. The spirals are thus arranged in two layers one over the other, as in Fig. 358, p. 364, with the effect that the commutator has virtually been turned through about a quadrant, so that the + brush will be on the left instead of at the top. This mode is adopted in the Edison-Hopkinson armatures amongst others. It has the advantage that all the spiral connectors front and back may be made of same size.

Fig. 193.



Drum Winding with Two Sets of Spiral Connectors.

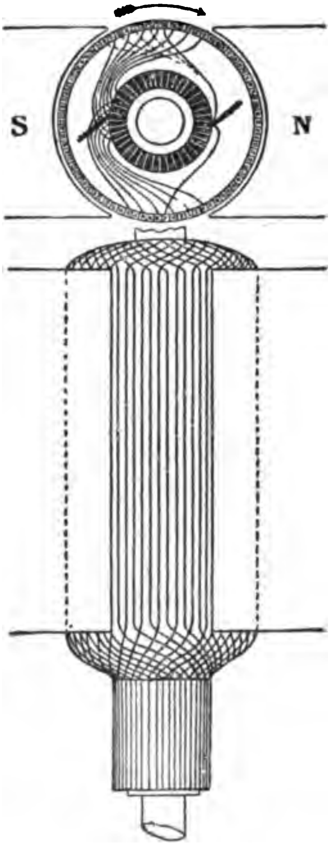
Fig. 194.



Two-layer Drum Winding.

If, however, the conductors are arranged in two layers, one over the other, the windings may be made across a diameter, the last turn being brought across to the next in the same layer. The conductors of the outer layer then answer instead of the intermediate members of the one-layer set. In Fig. 194 the end of No. 1 is brought to *a;* thence it spirals round to No. 21, which is connected across the back to No. 3, and so on. Fig. 195 shows how the 80 conductors of the Edison-Hopkinson armature (see p. 519) are connected, there being in reality two layers of 40 each, and a 40-part commutator.

FIG. 195.



DRUM WINDING OF EDISON-HOPKINSON DYNAMO.

DEVELOPED WINDING DIAGRAMS.

If one tries to draw all the connectors of a drum winding the lines cross and occasion confusion. There is therefore a great advantage in adopting a mode of representation, originally suggested by Herr Fritsche,[1] of Berlin, in which the armature winding is considered as though the entire structure had been developed out on a flat surface.

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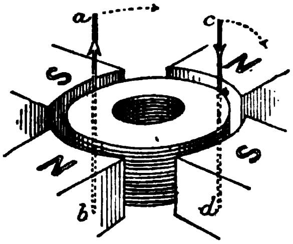
[1] *Centralblatt für Elektrotechnik*, ix. 649, 1887.

FIG. 196.



SKETCH OF 4-POLE FIELD

Consider first Fig. 196, which is a partial sketch of a four-pole machine laid on its side. The core, which may be hereafter wound either as ring or as drum, lies between the four poles of alternate polarity. If a copper rod *a* is placed parallel to the axis to represent one of the armature conductors, and is supposed to move along the gap-space right-handedly past the S pole, it will cut the magnetic lines entering that pole. By the rule given on p. 22, the induced electromotive-force in it will be upwards. Another conductor *c* passing the N pole will have induced in it a downward electromotive-force. If one was to attempt in a picture such as this to show twenty or more conductors and their respective connexions, the drawing would be unintelligible. Accordingly we have to imagine ourselves placed at the centre, and the panorama of the four poles around us to be then laid out flat, as in Fig. 197. It will be noticed that the faces of the N and S poles are shaded obliquely for distinction.[1]

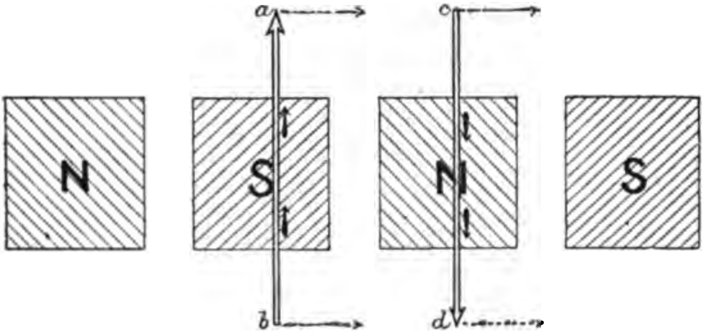
Now in an actual machine there are many armature conductors spaced symmetrically around, and these have to be grouped together by connecting wires. In the case of ring windings the wires which connect the active conductors in the gap-space pass through the central aperture in the ring when they are removed from the magnetic field. Suppose, for simplicity, we have a ring armature of only 12 turns, and

---

[1] I choose these oblique lines for the following reason. If instead of the line *a b* (representing a conductor), a narrow slit in a piece of paper were laid over the drawing of the pole-face, and moved as the dotted arrows show towards the right, the slit in passing over the oblique lines will cause an apparent motion in the direction in which the current tends in reality to flow. It is easy to remember which way the oblique lines must slope; for those on a N pole-face slope parallel to the oblique bar of the letter N.

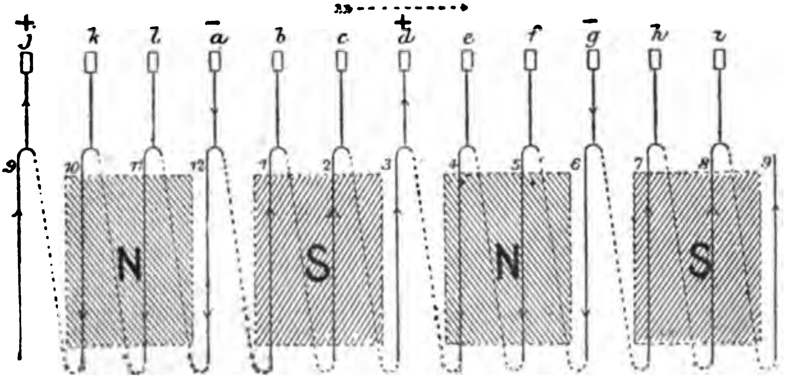
12 bars to the commutator. If this is opened out from the inside we shall have the form shown in Fig. 198 where the dotted lines are the inactive parts of the spiral winding that pass through the inside of the ring. By tracing the arrows it will be seen that there must be two positive and two negative brushes. Fig. 199 gives an end-view diagram of the same

FIG. 197.



4-POLE FIELD DEVELOPED FLAT.

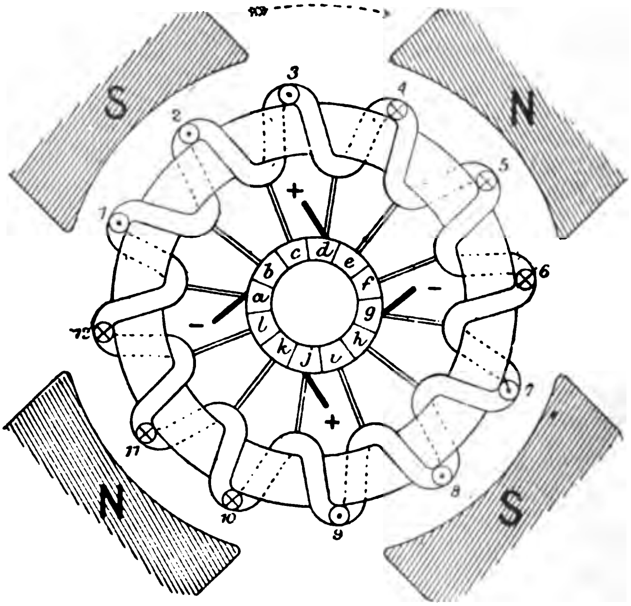
FIG. 198.



DEVELOPMENT OF RING WINDING FOR 4-POLE MACHINE.

winding, by which the two modes of presentation may be compared. It is clear that in this case the armature might be used as two separate machines to furnish two separate currents, though this would not be desirable. It is usual to couple the positive brushes together, and the negative brushes together. A 6-pole machine would require six brushes, and so forth. The reader should examine the cuts of the Berlin dynamos, Plate XI., and of the Edison multipolar ring machine, Plate XIII. When the brushes of the same sign are thus connected together the electromotive-force of the whole armature is simply that of any of the sets of coils from one + brush to the adjacent — brush. In this 4-pole machine the coils of the four quadrants are in four parallels; the internal resistance is one-fourth of the total resistance around

FIG. 199.



RING WINDING FOR 4-POLE MACHINE (CORRESPONDING TO FIG. 198).

the entire ring. There is, as we shall see, another mode of connecting the coils of a multipolar ring, in which the quadrants, instead of being all in parallel, are in series, so as to give two parallels only. This mode is sometimes called *multipolar series* winding; it would be more appropriately called *series-grouping*. It requires only two brushes, there being only two neutral points on the commutator, however many poles there are around the ring.

Returning to the method of development, and to Fig. 198, we have so far solved the problem of connecting the appropriate conductors by carrying the connecting conductor through the interior of a ring core, thus constituting a *spiral-winding*. When we go on to those cases in which the winding is entirely exterior to the core, as for drum armatures, or to those in which there is no core at all, namely for disk armatures, we find that there are two distinct modes of procedure, which we may respectively denote[1] as *lap-winding* and *wave-winding*. The distinction arises in the following manner. Since the conductors that are passing a north pole generate electromotive-forces in one direction, and those that are passing a south pole generate electromotive-forces in the opposite direction, it is clear that a conductor in one of these groups ought to be connected to one in nearly a corresponding position in the other group, so that the current may flow down one and up the other in agreement with the directions of the electromotive-forces. If now we examine Fig. 200 we shall see that at the back of the armature (or end distant from the commutator) each conductor is united to one five places further on—No. 1 to No. 6, No. 3 to No. 8—and that at the front end the winding, after having made one "element" (as for example *d*–7–12–*e*), then forms a second element (*e*–9–14–*f*), which laps over the first; and so on all the way round until the winding returns on itself.

Now contrast with this Fig. 201, in which, though the connexions at the back end are the same, those at the commutator end are different. It will be seen that when the winding returns back toward the commutator, instead of lapping back toward the part from which it started, it is

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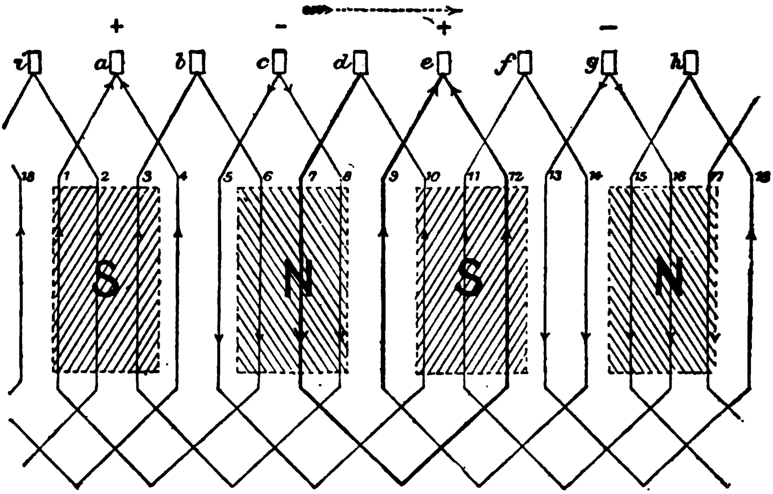
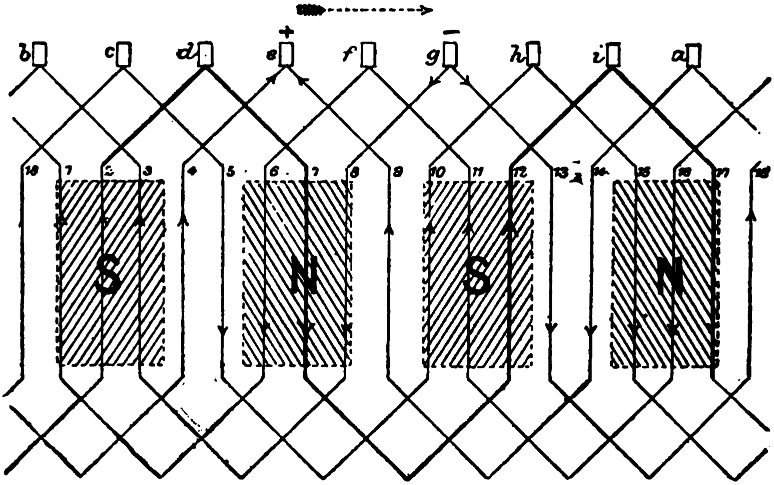
[1] **The wave-winding is Fritsche's *Wellen-wickelung;* the lap-winding is called by Arnold (*op. cit.*) *Scheitel-wickelung.***

Fig. 200.



Typical Lap-winding.

Fig. 201.



Typical Wave-winding.

turned the other way. The winding *d*–7–12 does not return at once to *e*, but goes on to *i*, whence another element *i*–17–4–*e* goes on in a sort of zig-zag wave. These are both drum windings, the corresponding tables being as follows:—

Winding-table for Fig. 200.
(Lap-winding.)

F	B		F
+ *a*	1	6	*b*
b	3	8	*c*
— *c*	5	10	*d*
d	7	12	*e*
+ *e*	9	14	*f*
f	11	16	*g*
— *g*	13	18	*h*
h	15	2	*i*
i	17	4	*a*

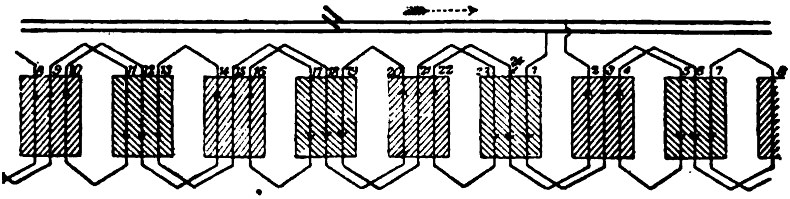
Winding-table for Fig. 201.
(Wave-winding.)

F	B		F
a	1	6	*f*
f	11	16	*b*
b	3	8	*g*
— *g*	13	18	*c*
c	5	10	*h*
h	15	2	*d*
d	7	12	*i*
i	17	4	*e*
+ *e*	9	14	*a*

It will be noted in passing that whilst with this particular number of conductors (18) the lap-winding results in four parallels of coils, and needs four brushes, the wave-winding results in two parallels, and requires two brushes only.

Before going on to other drum-windings it may be remarked that the same distinction between lap-windings and wave-windings is applicable to alternate current machines. These are usually multipolar. In Fig. 202 is an 8-pole alternator with lap-winding, each "element" or set of loops

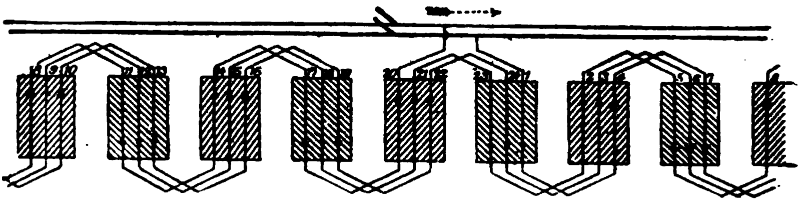
Fig. 202.



Alternate Current Machine : Lap-winding.

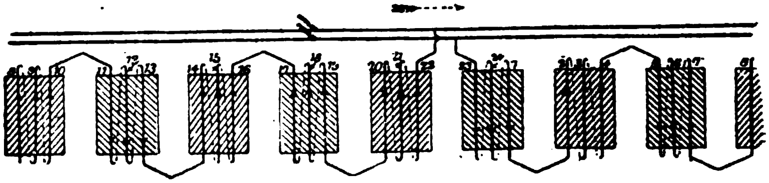
extending across the same breadth as the "pitch" or distance from centre to centre of two adjacent poles. Only 24 conductors have been drawn; and it will be noticed that the successive loops are alternately right-handed and left-handed. In Fig. 203 is shown the same alternator with a wave-winding. The electromotive-force of the two machines would be precisely the same; the choice between the two methods of connecting is here purely a question of mechanical convenience in construction and cost. A ring-winding suitable for alternate currents is developed in Fig. 204; also for an 8-pole field. It should be compared with Figs. 202 and 203.

FIG. 203.



ALTERNATE CURRENT MACHINE: WAVE-WINDING.

FIG. 204.



ALTERNATE CURRENT MACHINE: RING-WINDING.

WINDING FORMULÆ FOR CLOSED COIL ARMATURES.

General formulæ for connecting—applicable chiefly to drum-windings—have been given by Hopkinson and by Arnold. We shall follow the latter in the main. Let C stand for the number of conductors as arranged around the armature core. Let p stand for the number of pairs of poles so that the actual number of poles is $2p$. Let b stand for the number of active conductors in any one "element" of the winding, s for the number of sections, and c for the number of bars in the commutator. Clearly in ring-windings b is the number of turns in a section. Let the numerical step by which one advances in connecting up the conductors from one section to another be called y (for example, if No. 8 section is connected to No. 15, then $y = 7$). This number y, since it represents the number of spaces between the sections that are bridged over, may be called the "*spacing.*" It must always be, relatively to s, a prime number, otherwise the winding will not be re-entrant as a closed coil. If they have a common factor (as, for example, $s = 36$, $y = 27$, where the common factor is 3) there will be as many *independent* circuits.

Such independent circuits have been used by Weston, and by Messrs. Siemens Bros. Armatures so wound require broad brushes covering at least two segments of the commutator.

Arnold's formulæ connecting these quantities are

$$y = \frac{1}{p}\left(\frac{C}{b} \mp a\right);$$
$$C = b\,(p\,y \pm a);$$

wherein a is a certain whole number (often $= 1$) on the value of which depends the number of bifurcations of the current through sets of coils that are in parallel with one another. The number of neutral points on the commutator will be always $= 2\,a$. In applying the formulæ we have several cases to deal with.

(*i.*) *Parallel Grouping.* As we have seen in the case of an ordinary ring in a 4-pole field, there will be four rows of $\frac{C}{4}$ coils each in parallel with one another. In a 2-pole field there are two rows of $\frac{C}{2}$ each. In a 12-pole field we should have 12 rows of $\frac{C}{12}$ each, in parallel. As we have seen above in the case of the 4-pole ring with spiral-winding, each pair of such rows may be considered as constituting a separate 2-pole armature. It is also so for drum armatures if wound with lap-windings, but not if with wave-windings. The two cases stand thus:—

(*a*) *With Spiral-winding or Lap-winding* write in the formula $p = 1$ and $a = 1$, and apply it to a set of conductors lying between two poles of similar name.

(*b*) *With Wave-winding* write $a = p$; that is to say, there must be as many bifurcations of the current as there are pairs of poles. In a 6-pole machine $p = 3$, and the current will bifurcate at three points (the three negative brushes), going through six parallel paths to the three positive brushes (or to the cross connexions that lead to the positive brush).

(*ii.*) *Series Grouping.* For this, seeing that the current only bifurcates once, $a = 1$, whatever the mode of coiling. In the case of 2-pole machines the series grouping and parallel grouping are the same thing—there are two rows of coils in parallel with one another, and the winding may be either a wave-winding or a lap-winding; or, as will be seen, a spiral-winding may be used for ring machines. For 4-pole machines the same holds good. For machines having more poles than four, however, the only possible cases of series grouping are wave-windings.

(*iii.*) *Mixed Groupings.* There are several possible cases of mixed lap- and wave-windings, corresponding to cases where $a > 1$ or $a \gtrless p$.

As examples for verifying these formulæ we may take the following:—

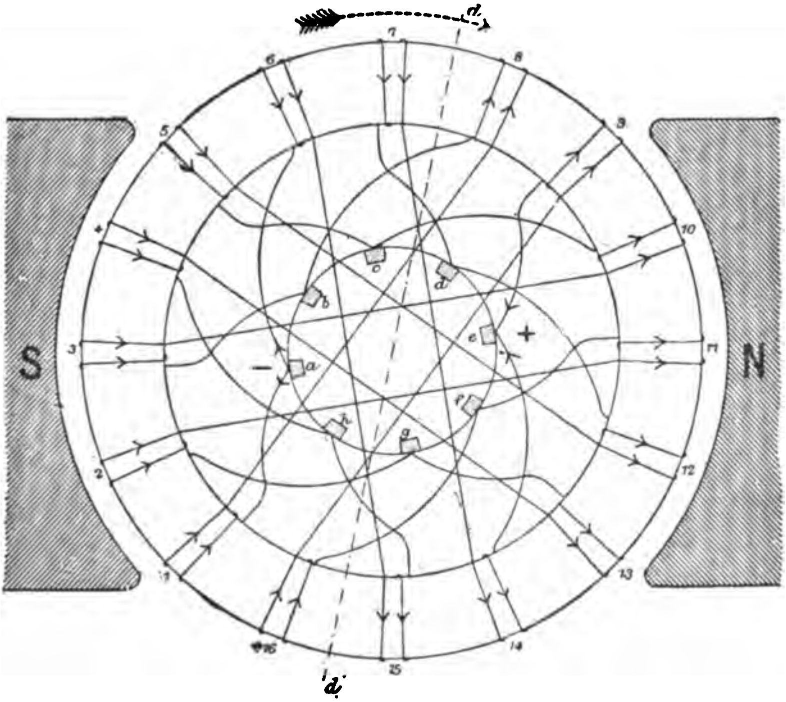
In the ring-winding Fig. 34, p. 40 $C = 32$; $p = 1$; $b = 4$; $s = 8$; $c = 8$. Hence $y = 7$ or 9. But the ring has eight sections only, of which, therefore, the seventh and the ninth, reckoned from any given section, are those that lie on either side of it.

In the drum-winding, Fig. 70, p. 90, $C = 32$; $p = 1$;

$b = 2$ (because each "element" of the winding from bar to bar of the commutator contains two active conductors); $s = 16$; $c = 16$. Hence $y = 15$ or 17. The former number may be taken as referring to the front layer of connexions (No. 1 to No. 16), the latter to the layer below them (No. 2 to No. 19.)

A further example is afforded by a special ring-winding used by Wodicka, Fig. 205, in which each section is joined in series with one on the side opposite to it, so that the number of commutator bars is half that of the sections. Here each "element" of the winding consists of two sections, each containing active conductors; hence $b = 4$; $C = 32$; $s = 16$; $p = 1$; whence y may be either 9 or 7.

FIG. 205.

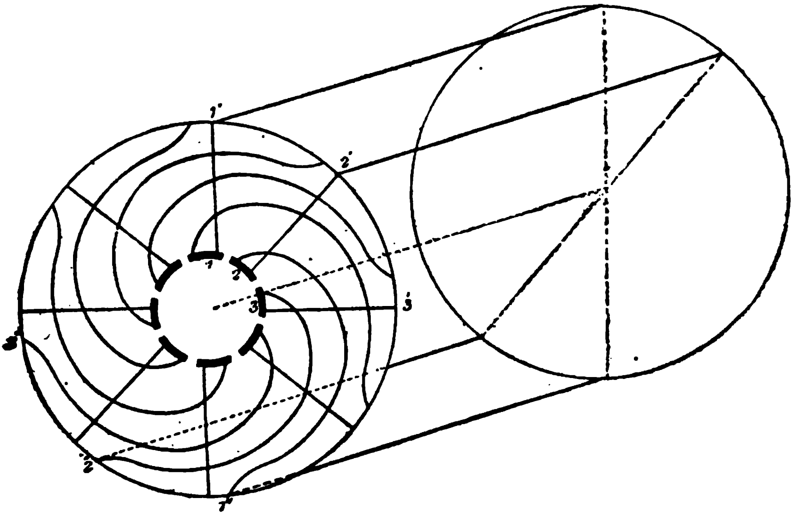


RING-WINDING WITH OPPOSITE COILS IN SERIES.

DRUM-WINDINGS.

In Fig. 206 is given a drawing of drum-winding applied to an 8-part armature. As in all Siemens' earlier drums the windings lay in two layers, each section being wound diametrically. Thus starting from the bar of the commutator marked 1 we pass outwards to 1′, then down the armature, across the back, up to 1″, and (after having wound a sufficient number of turns to form a section) spiral up to bar 2 of the commutator. In the original specification of Siemens' patent the end connexions were unsymmetrical, as shown in Fig. 207. The Edison variety of Siemens' winding is shown in Fig. 208. The diagram only shows a simple case with a 7-part commutator. Here $C=14$; $b=2$; and according to the formula y should be 6. But the actual value of the spacing is 7 at the back and 5 at the front end, as will be seen. With an odd number of sections commutation does

FIG. 206.

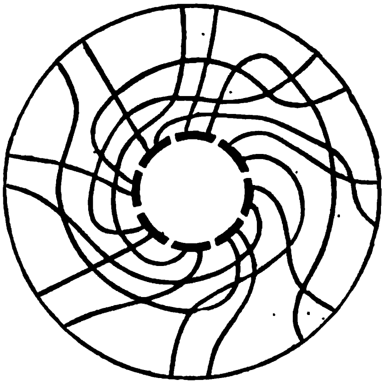


CONNEXIONS OF SIEMENS, (VON HEFNER ALTENECK) WINDING.

not occur simultaneously (in 2-pole machines) at both the brushes, but alternately.

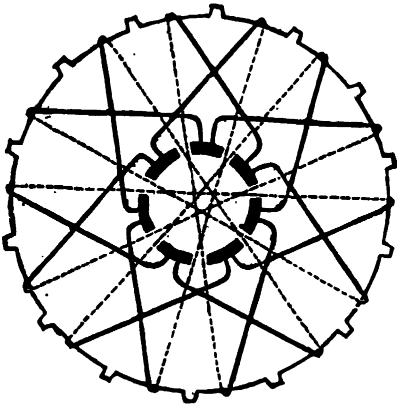
A closer study of the drum-winding is important, and accordingly there are given a series of winding diagrams relating to several varieties.

Fig. 207.



Connexions of Siemens Winding (Old.)

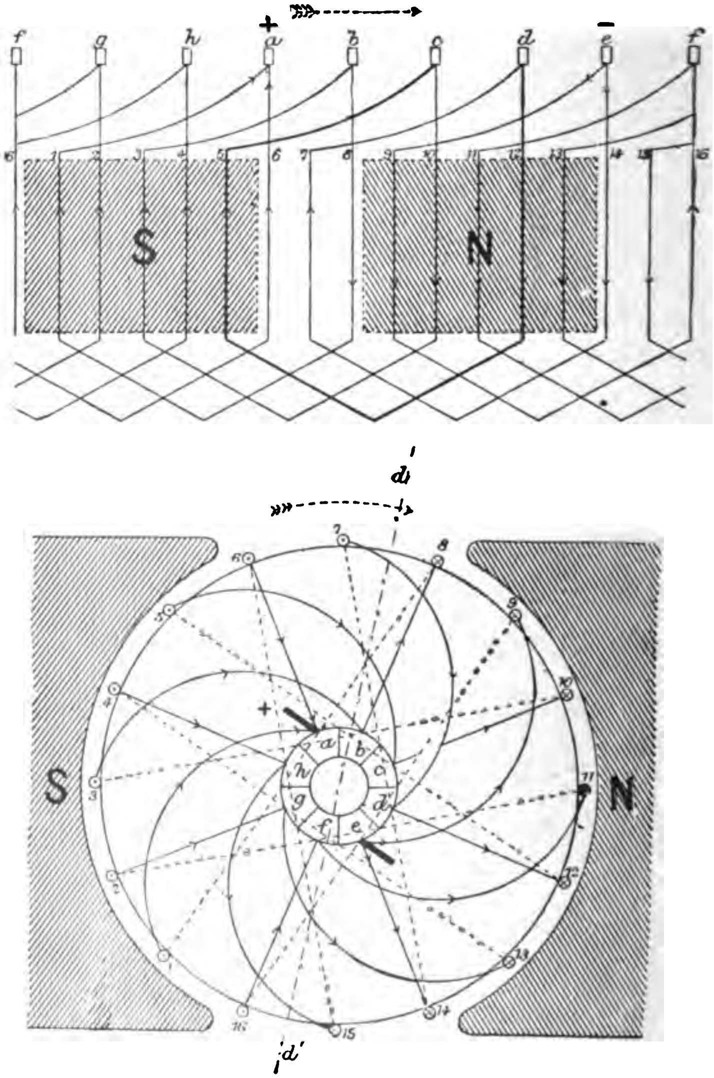
Fig. 208.



Connexions of Edison Winding.

In Figs. 209 and 210 are given a right-handed winding on Siemens' plan for an 8-part commutator, and one turn to

Figs. 209 and 210.



Lap-winding (Siemens' Right-handed) Development and End View.

each section, *i.e.* with 16 conductors spaced round the periphery. The connecting pieces at the front end consist of straight connectors (such as *a* 6)and spiral connectors (such as *a* 1) which cross (either under or over) the former. The connecting pieces at the back end are not further indicated than by the dotted lines drawn across. In the developed diagram it is shown that each element of the winding is similar to *c*–5–12–*d*, and that the arrangement is a lap-winding. The back connectors space over seven conductors, being just short by one of the number $\frac{C}{2}$ in the semi-circumference; whilst the front connectors space over five, being short by three of the semi-circumference. It will be further noted that with this right-handed winding, rotating right-handedly in a right-handed field, the + brush is near the top of the commutator.

Figs. 211 and 212 represent the same thing, except that the winding is left-handed, with the result that the + brush is now near the bottom of the commutator.

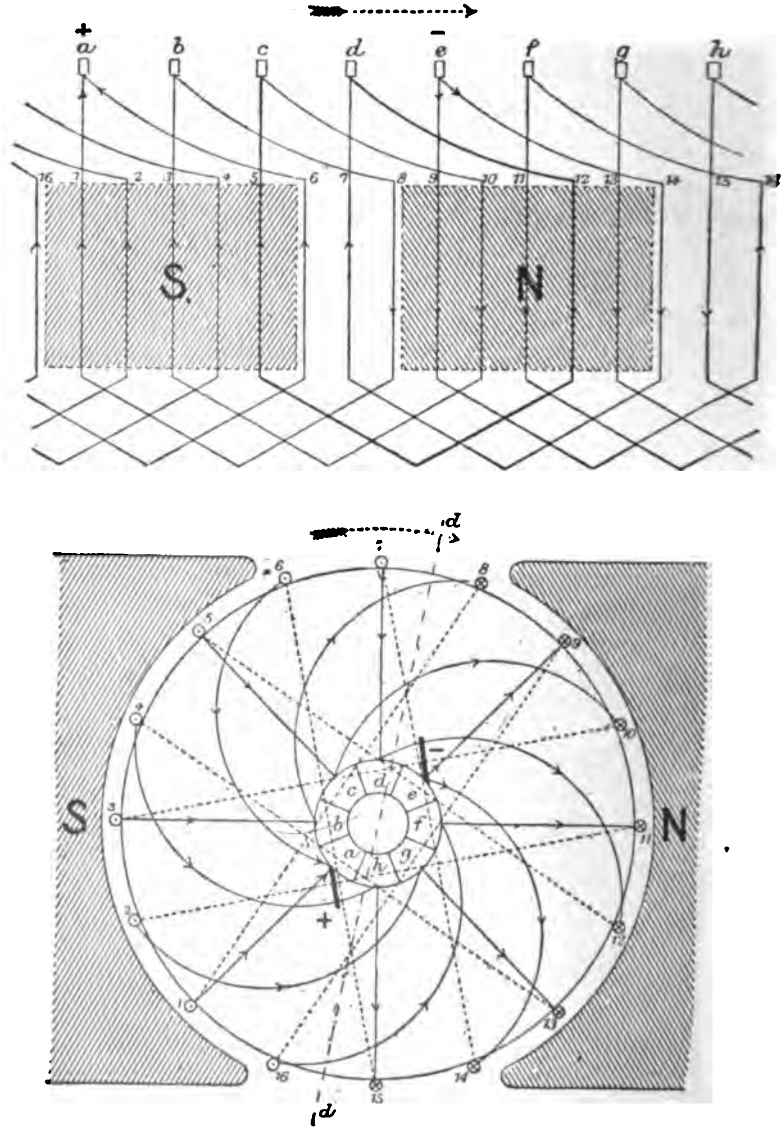
The winding table for both these Figures is the same, namely:—

F	B		F
+ *a*	1	8	*b*
b	3	10	*c*
c	5	12	*d*
d	7	14	*e*
— *e*	9	16	*f*
f	11	2	*g*
g	13	4	*h*
h	15	6	*a*

But in the right-handed winding the spiral connectors, such as *a* to 1, go toward the left, and in the left-handed winding to the right.

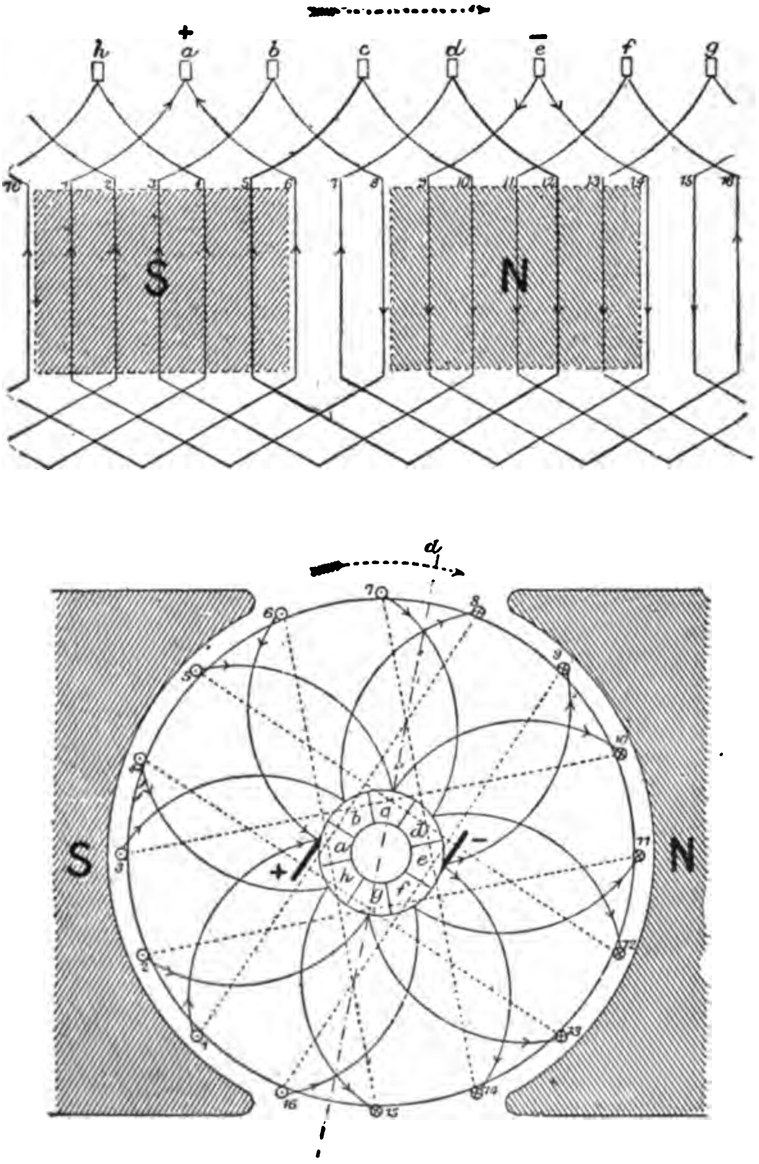
In Fig. 209 and Fig. 211 (the developments) it is seen that for both these windings the "element" of the winding,

Fig. 211 and 212.



Lap-winding (Siemens' Left-handed) Development and End View.

Fig. 213 and 214.



Lap-winding (2-pole Symmetrical) Development and End View.

indicated by the darker lines, is unsymmetrical at the front end of the drum, this being due to the use of two sorts of front connectors, one straight, one spiral. The bar *a* of the commutator is connected to the front ends of conductors No. 1 and No. 6. In one case it is skewed forward to be opposite No. 6; in the other it is skewed backward to be opposite No. 1. Why should it not be placed symmetrically between them?

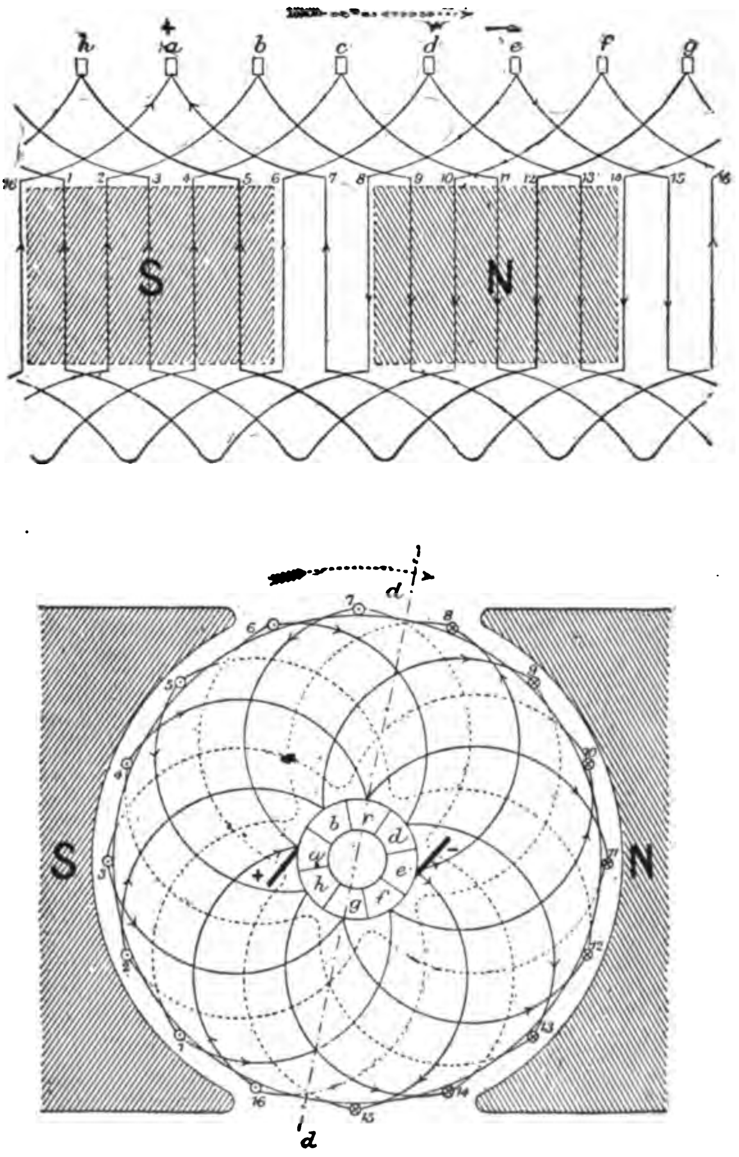
Figs. 213 and 214 depict a symmetrical lap-winding, electrically precisely equivalent to the preceding, and having the same winding table. The advantages are twofold: that (for built-up armatures) the connectors at the front end are now all of the same pattern, consisting of two sets of short spirals; and that the brushes now come to a horizontal diameter where they are more accessible. The back connexions remain exactly as before, and go across a longer chord than the front connexions.

To secure the utmost symmetry in the winding, the back and front connectors ought to be equalized. The theoretically proper spacing is $y = 7$ or $y = 9$. To attain this, join No. 1 to No. 8 at one end of the drum and to No. 10 at the other. The result is shown in Figs. 215 and 216, from which it is at once apparent that we have passed from lap-windings to a wave-winding; each element passing around the drum and returning only to the next bar of the commutator from whence it started. The winding-table for this case is:—

F		B	F
+ *a*	16	9	*b*
b	2	11	*c*
c	4	13	*d*
d	6	15	*e*
— *e*	8	1	*f*
f	10	3	*g*
g	12	5	*h*
h	14	7	*a*

Electrically, this winding is the precise equivalent of the

FIGS. 215 and 216.

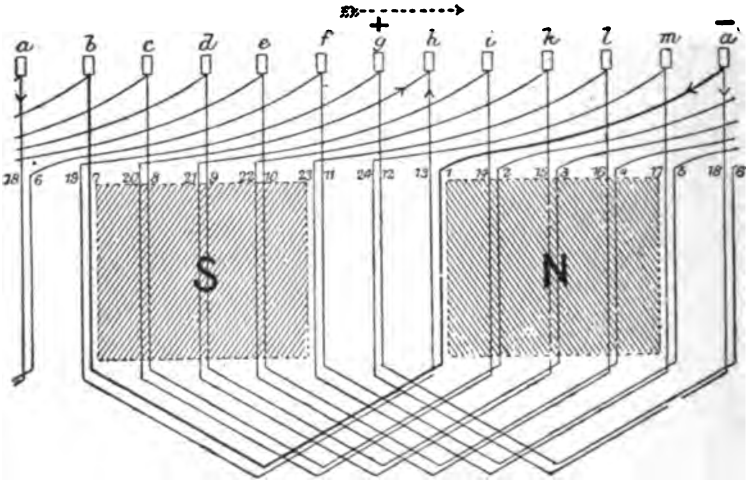


WAVE-WINDING (2-POLE SYMMETRICAL) DEVELOPMENT AND END VIEW.

three preceding. The spiral connectors at the back end meet in pairs as those at the front meet at the commutator.

A two-layer winding for twenty-four conductors, together with its development, are given in Figs. 217 and 218, showing how, when half the armature, from *a* to *g*, has been completed one layer has been wound.

FIG. 217.



TWO LAYER DRUM-WINDING.

Multipolar Drums.—As mentioned on p. 337 below, the winding of multipolar armatures with series-grouping was suggested by Professor Perry.[1] It has been applied to drum-winding by Messrs. Paris and Scott,[2] and by Mr. Kapp. For the case of multipolar machines it is convenient to state the rule in words that if a series grouping (so as to give high voltage) is desired, y must be an odd number and that the total number of conductors must be equal to y times the whole number of poles, plus or minus two. For example; for a 6-pole drum, taking y as 15, the number of conductors must be either 88 or 92; not 90. Below is given a winding-table,

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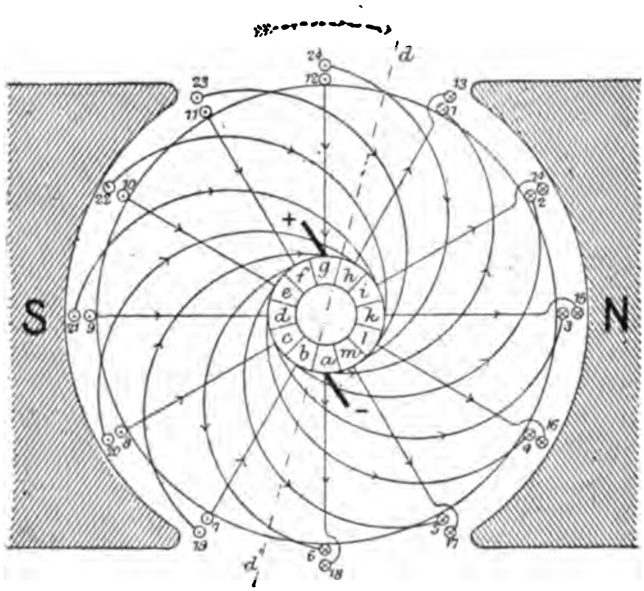
[1] Specification of Patent, No. 3036 of 1882.

[2] Specification of Patent, No. 4683 of 1884.

FIG. 218.

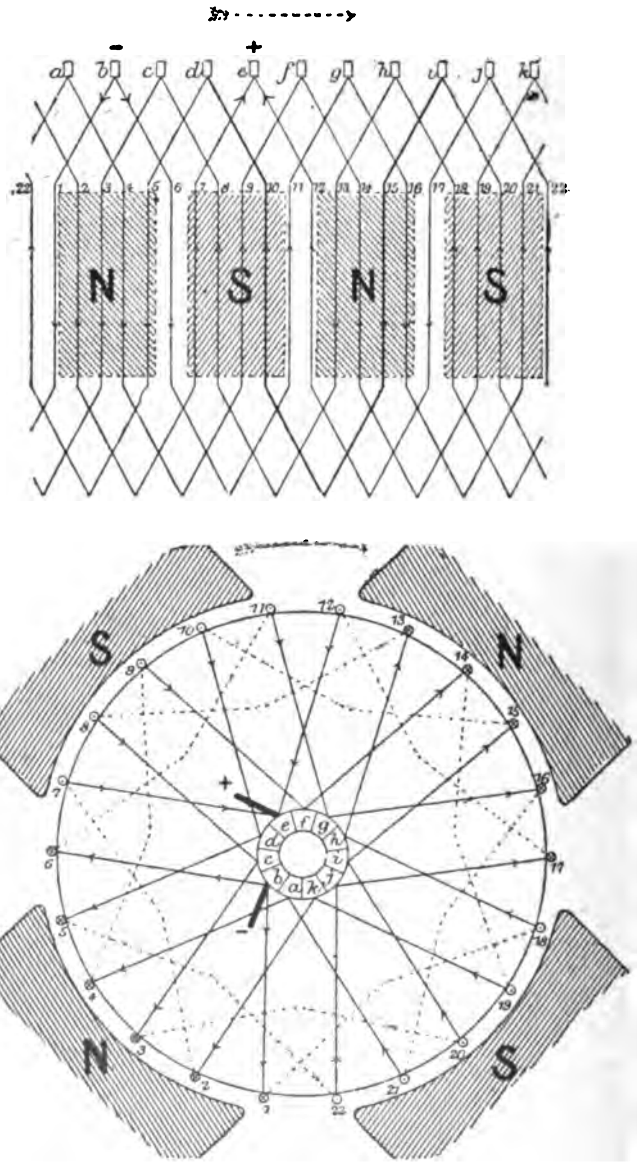


TWO LAYER DRUM-WINDING.

calculated by Mr. Kapp for an 8-pole machine having a spacing of $y = 25$.

It may be remarked in passing that if in multipolar machines the number of sections is an exact multiple odd or even of p, the grouping will be parallel: and if it is an odd multiple then commutation will not occur simultaneously at all the brushes, but alternately at all the + brushes and at all

Fig. 219 and 220.



Multipolar Drum-winding : Series Grouping.

the – brushes, similarly to the alternate commutation in a 2-pole machine when there is an odd number of sections in the winding.

WINDING TABLE FOR 8-POLE DRUM ARMATURE; 202 CONDUCTORS; SERIES GROUPING; BRUSHES (±) 135° APART.

<table>
<tr><th>F</th><th colspan="2">B</th><th colspan="2">F</th><th colspan="2">B</th><th colspan="2">F</th><th colspan="2">B</th><th colspan="2">F</th><th colspan="2">B</th><th>F</th></tr>
<tr><th colspan="2">D</th><th colspan="2">U</th><th colspan="2">D</th><th colspan="2">U</th><th colspan="2">D</th><th colspan="2">U</th><th colspan="2">D</th><th colspan="2">U</th></tr>
<tr><td colspan="2">202</td><td colspan="2">25</td><td colspan="2">50</td><td colspan="2">75</td><td colspan="2">100</td><td colspan="2">125</td><td colspan="2">50</td><td colspan="2">175</td></tr>
<tr><td colspan="2">200</td><td colspan="2">23</td><td colspan="2">48</td><td colspan="2">73</td><td colspan="2">98</td><td colspan="2">123</td><td colspan="2">148</td><td colspan="2">173</td></tr>
<tr><td colspan="2">198</td><td colspan="2">21</td><td colspan="2">46</td><td colspan="2">71</td><td colspan="2">96</td><td colspan="2">121</td><td colspan="2">146</td><td colspan="2">171</td></tr>
<tr><td colspan="2">196</td><td colspan="2">19 –</td><td colspan="2">44</td><td colspan="2">69</td><td colspan="2">94</td><td colspan="2">119</td><td colspan="2">144</td><td colspan="2">169</td></tr>
<tr><td colspan="2">194</td><td colspan="2">17</td><td colspan="2">42</td><td colspan="2">67</td><td colspan="2">92</td><td colspan="2">117</td><td colspan="2">142</td><td colspan="2">167</td></tr>
<tr><td colspan="2">192</td><td colspan="2">15</td><td colspan="2">40</td><td colspan="2">65</td><td colspan="2">90</td><td colspan="2">115</td><td colspan="2">140</td><td colspan="2">165</td></tr>
<tr><td colspan="2">190</td><td colspan="2">13</td><td colspan="2">38</td><td colspan="2">63</td><td colspan="2">88</td><td colspan="2">113</td><td colspan="2">138</td><td colspan="2">163</td></tr>
<tr><td colspan="2">180</td><td colspan="2">11</td><td colspan="2">36</td><td colspan="2">61</td><td colspan="2">86</td><td colspan="2">111</td><td colspan="2">136</td><td colspan="2">161</td></tr>
<tr><td colspan="2">186</td><td colspan="2">9</td><td colspan="2">34</td><td colspan="2">59</td><td colspan="2">84</td><td colspan="2">109</td><td colspan="2">134</td><td colspan="2">159</td></tr>
<tr><td colspan="2">184</td><td colspan="2">7</td><td colspan="2">32</td><td colspan="2">57</td><td colspan="2">82</td><td colspan="2">107</td><td colspan="2">132</td><td colspan="2">157</td></tr>
<tr><td colspan="2">182</td><td colspan="2">5</td><td colspan="2">30</td><td colspan="2">55</td><td colspan="2">80</td><td colspan="2">105</td><td colspan="2">130</td><td colspan="2">155</td></tr>
<tr><td colspan="2">180</td><td colspan="2">3</td><td colspan="2">28</td><td colspan="2">53</td><td colspan="2">78</td><td colspan="2">103</td><td colspan="2">128</td><td colspan="2">153</td></tr>
<tr><td colspan="2">178</td><td colspan="2">1</td><td colspan="2">26</td><td colspan="2">51</td><td colspan="2">76</td><td colspan="2">101</td><td colspan="2">126</td><td colspan="2">151</td></tr>
<tr><td colspan="2">176</td><td colspan="2">201</td><td colspan="2">24</td><td colspan="2">49</td><td colspan="2">74</td><td colspan="2">99</td><td colspan="2">124</td><td colspan="2">149</td></tr>
<tr><td colspan="2">174</td><td colspan="2">199</td><td colspan="2">22</td><td colspan="2">47</td><td colspan="2">72</td><td colspan="2">97</td><td colspan="2">122</td><td colspan="2">147</td></tr>
<tr><td colspan="2">172</td><td colspan="2">197</td><td colspan="2">20</td><td colspan="2">45</td><td colspan="2">70</td><td colspan="2">95 +</td><td colspan="2">120</td><td colspan="2">145</td></tr>
<tr><td colspan="2">170</td><td colspan="2">195</td><td colspan="2">18</td><td colspan="2">43</td><td colspan="2">68</td><td colspan="2">93</td><td colspan="2">118</td><td colspan="2">143</td></tr>
<tr><td colspan="2">168</td><td colspan="2">193</td><td colspan="2">16</td><td colspan="2">41</td><td colspan="2">66</td><td colspan="2">91</td><td colspan="2">116</td><td colspan="2">141</td></tr>
<tr><td colspan="2">166</td><td colspan="2">191</td><td colspan="2">14</td><td colspan="2">39</td><td colspan="2">64</td><td colspan="2">89</td><td colspan="2">114</td><td colspan="2">139</td></tr>
<tr><td colspan="2">164</td><td colspan="2">189</td><td colspan="2">12</td><td colspan="2">37</td><td colspan="2">62</td><td colspan="2">87</td><td colspan="2">112</td><td colspan="2">137</td></tr>
<tr><td colspan="2">162</td><td colspan="2">187</td><td colspan="2">10</td><td colspan="2">35</td><td colspan="2">60</td><td colspan="2">85</td><td colspan="2">110</td><td colspan="2">135</td></tr>
<tr><td colspan="2">160</td><td colspan="2">185</td><td colspan="2">8</td><td colspan="2">33</td><td colspan="2">58</td><td colspan="2">83</td><td colspan="2">108</td><td colspan="2">133</td></tr>
<tr><td colspan="2">158</td><td colspan="2">183</td><td colspan="2">6</td><td colspan="2">31</td><td colspan="2">56</td><td colspan="2">81</td><td colspan="2">106</td><td colspan="2">131</td></tr>
<tr><td colspan="2">156</td><td colspan="2">181</td><td colspan="2">4</td><td colspan="2">29</td><td colspan="2">54</td><td colspan="2">79</td><td colspan="2">104</td><td colspan="2">129</td></tr>
<tr><td colspan="2">154</td><td colspan="2">179</td><td colspan="2">2</td><td colspan="2">27</td><td colspan="2">52</td><td colspan="2">77</td><td colspan="2">102</td><td colspan="2">127</td></tr>
<tr><td colspan="2">152</td><td colspan="2">177</td><td colspan="2">202</td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td></tr>
</table>

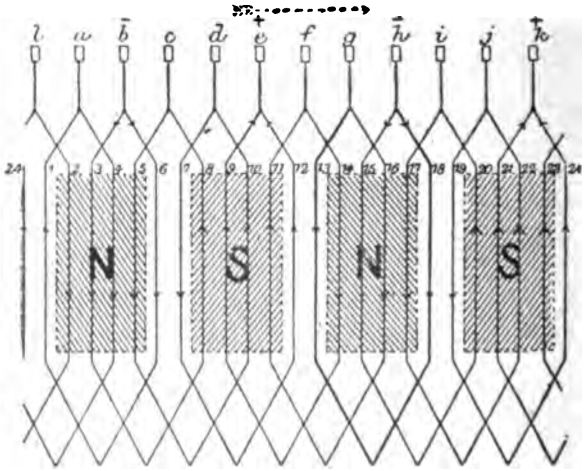
In Figs. 219 and 220 are given the connexions for a 4-pole drum winding with twenty-two conductors; here $y = 5$. The winding-table for this armature is as follows:—

4-POLE DRUM : 22 CONDUCTORS : SERIES GROUPING.

<table>
<tr><td colspan="2">F</td><td colspan="2">B</td><td colspan="2">F</td><td colspan="2">B</td><td colspan="2">F</td></tr>
<tr><td></td><td colspan="2">D</td><td colspan="2">U</td><td colspan="2">D</td><td colspan="2">U</td><td></td></tr>
<tr><td></td><td colspan="2">1</td><td colspan="2">18</td><td colspan="2">13</td><td colspan="2">8</td><td></td></tr>
<tr><td></td><td colspan="2">3</td><td colspan="2">20</td><td colspan="2">15</td><td colspan="2">10</td><td></td></tr>
<tr><td></td><td colspan="2">5</td><td colspan="2">22</td><td colspan="2">17</td><td colspan="2">12 +</td><td></td></tr>
<tr><td></td><td colspan="2">+ 7</td><td colspan="2">2</td><td colspan="2">19</td><td colspan="2">14</td><td></td></tr>
<tr><td></td><td colspan="2">9</td><td colspan="2">4</td><td colspan="2">21</td><td colspan="2">16</td><td></td></tr>
<tr><td></td><td colspan="2">11</td><td colspan="2">6</td><td colspan="2">— 1</td><td colspan="2"></td><td></td></tr>
</table>

In Figs. 221 and 222 is given a lap-winding used by Thury (see Fig. 362, p. 534), the case illustrated being that of a 4-pole drum. It is a lap-winding for parallel grouping, with a spacing at the back end just short of the pitch of the poles and a still shorter spacing at the front end. This is a form of chord winding intended to keep conductors at very dif-

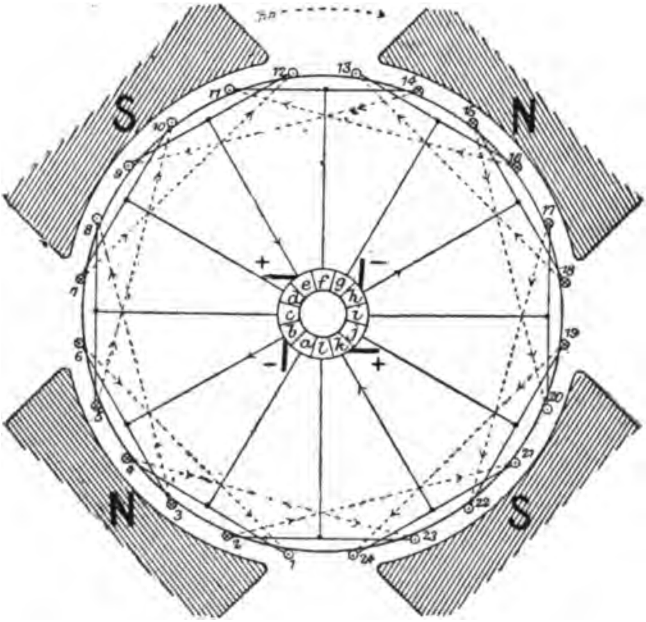
FIG. 221.



THURY'S ARMATURE (4-POLE LAP-WINDING).

ferent potentials from overlapping, and it can be well insulated because the separate sections can be wound on formers before being laid over the core.

FIG. 222.



THURY'S ARMATURE (4-POLE LAP-WINDING).

In Figs. 223 and 224 are shown two more complex windings due to Alioth.[1] In Fig. 223, which relates to a parallel grouping, the current entering at the negative brush bifurcates twice, finding four paths through the windings, two of the coils being short-circuited alternately at the + and − brushes. In Fig. 224 the connexions are rearranged so as to give only one bifurcation, and therefore only two rows of windings.

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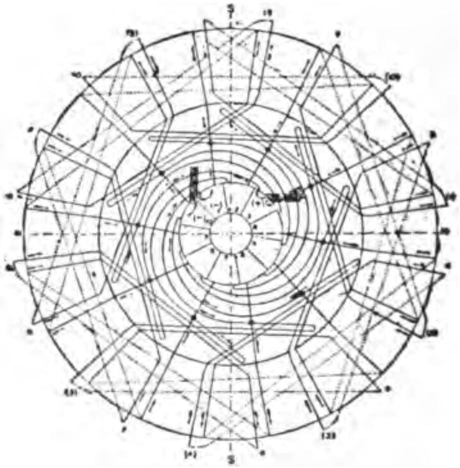
[1] See *Electrician*, xxiv. 140, Dec. 13, 1889, article by A. T. Snell.

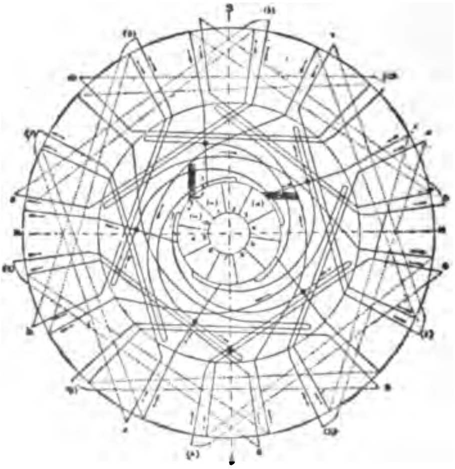
A method of drum-winding was proposed by Fritsche,[1] in which the conductors all lie obliquely across the surface of the

FIG. 223.



ALIOTH'S 4-POLE WINDING. PARALLEL GROUPING IN FOUR ROWS.

FIG. 224.



ALIOTH'S 4-POLE WINDING. SERIES GROUPING IN TWO ROWS.

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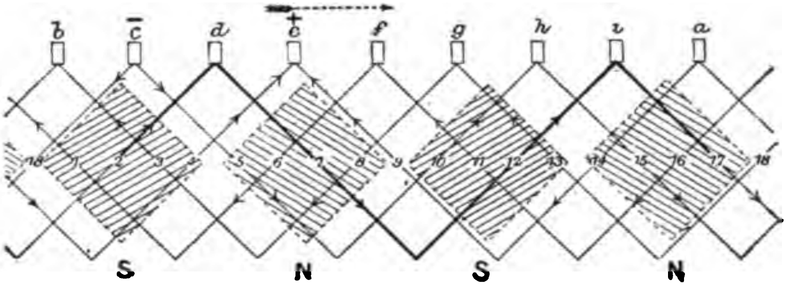
[1] *Op. Citat.*

drum, no part of them being parallel to the shaft. In this case the field-magnet poles are also constructed with diagonal faces. This oblique winding is shown developed in Fig. 225;

Fig. 225.



Fritsche's Oblique Wave-winding.

which should be compared with the winding of Fig. 201, to which it is electrically equivalent.

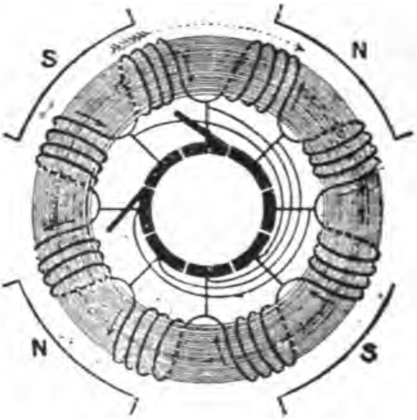
Multipolar drum-windings have also been proposed by Hopkinson and by Bradley.

MULTIPOLAR RING WINDINGS.

Of these something has been already said on p. 310. It was noted that an ordinary ring placed in a multipolar field would have as many neutral-points on its commutator as there are poles around it, and would therefore need as many brushes as the machine had poles. It is, however, possible to reduce the number of brushes to two, by two independent methods, one of which connects the rows of sections in parallel with multiple paths throughout the ring, the other puts them in series with but two paths through the ring.

In Fig. 226 is represented a mode of reducing the number of brushes to two, by cross-connecting windings at opposite sides of the ring, a device due to Mr. Mordey. This may be looked upon as simply putting into parallel with one another each coil and the one that occupies the similar place opposite the corresponding pole. The arrangement looks unsymmetrical, but is not really so. For a 6-pole machine each coil would need to be connected with the two others at 120° on either side of it. There are several actual ways of doing this. One is by means of spiral connectors; another is by connecting across the corresponding bars of the commutator. In the Victoria dynamos of the Brush Company (p. 479) the length of shaft between the ring and the commutator permits of double cross-connexion, each junction of two adjacent sections being connected by a wire down to the nearest bar of the commutator, and also connected round to that on the opposite side, as in Fig. 227. In some of the Gülcher Company's dynamos the cross-connexion is effected by a series of metal rings threaded on an insulated sleeve over the shaft, each such ring having two diametrical lugs which cross-connect the wires leading down to opposite bars of the commutator. Such cross-connected machines really have four neutral points, but the brushes collect the current from two only.

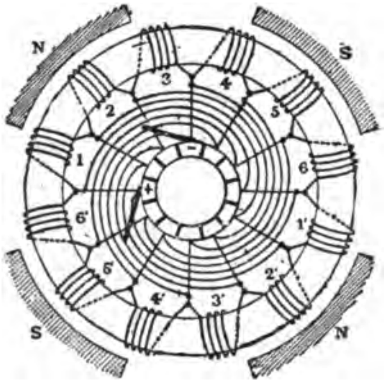
Fig. 226.



Mordey's Method of Multipolar Connexions of Ring (Parallel Connexions).

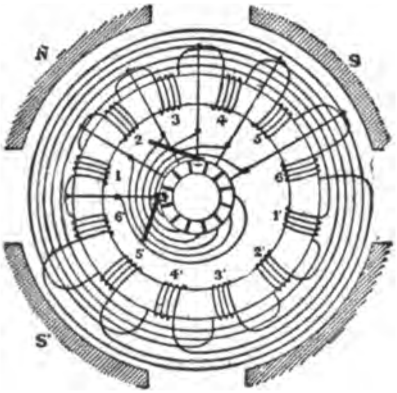
There are several methods of grouping the windings in series so as to gain a double electromotive-force. One of these modes, electrically symmetrical, is depicted in Fig. 228, wherein, while opposite coils are coupled in series, the commutator bars are cross-connected. This requires also but two brushes, at 90° apart. Two other modes of accomplishing the

Fig. 227.



Connexions of Victoria (Mordey) 4-pole Armatures.

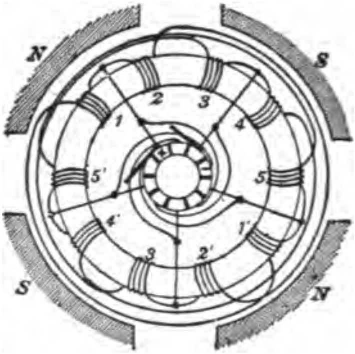
Fig. 228.



4-pole Ring, Series Grouping (2 Rows).

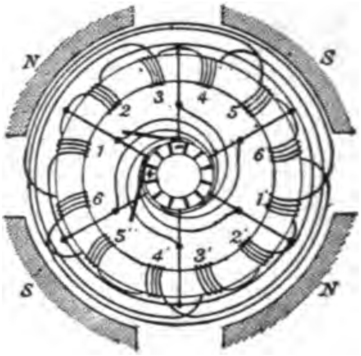
same end are shown in the windings of Figs. 229 and 230. Here, however, the connexions are not symmetrical, so that the resistances of the two paths (and therefore the respective currents) cannot be at all instants equal.

Fig. 229.



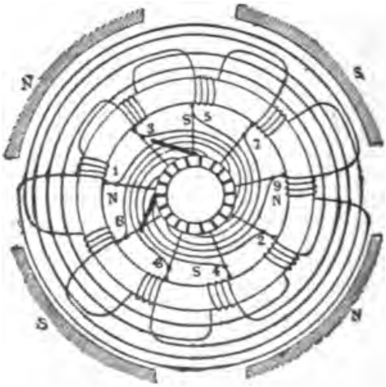
4-pole Ring, Series Grouping (2 Rows).

Fig. 230.



4-pole Ring, Series Grouping (2 Rows).

Fig. 231.

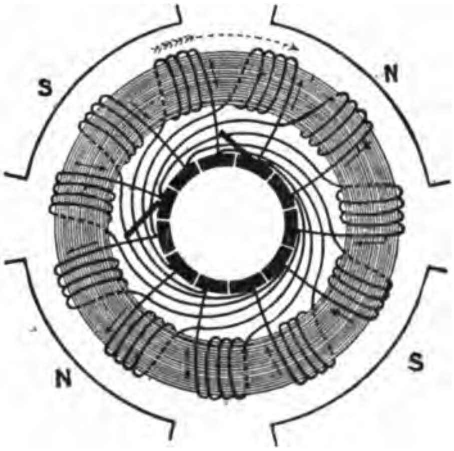


Multipolar Ring.

In yet another arrangement (Fig. 231), each coil is connected down to p segments at intervals of $\frac{360^\circ}{p}$ around the ring; and introduces an increased number of bars of the commutator.

Another winding, devised by Professor Perry, brings down the connexions from each section across a chord of the commutator. The case shown is that of a ring with eleven sections in a 4-pole field. The number of sections and of parts of the commutator must be odd if the number of pairs of poles is even. It may be either odd or even for 6-pole or 10-pole machines. Arnold points out that it is given by the formula:

FIG. 232.



PERRY'S METHOD OF MULTIPOLAR SERIES-GROUPING.

$$S = p\,y \pm 1.$$

Arnold[1] has described numerous other ring windings of complex kinds.

DISK WINDINGS.

These may in general be treated as drum windings extended radially, the outer periphery corresponding to the back end of the drum. The earliest such winding is that suggested in 1875, by Pacinotti. This is a lap-winding adapted for a 2-pole field, the N pole being behind the upper part, the S pole behind the lower part in the cut. It will be noted that the outer end of each radial conductor is carried round by a peripheral connecting piece to join the end of another radial conductor, which for a 2-pole machine would be the one lying next but one to that which is diametrically opposite. The schematic figure relates to a 10-part armature, made up of twenty radial conductors. They are numbered so that the order of connexions may be traced. The diameter of commutation being *d d*, the currents flow radially inwards in one half and radially outwards in the other half of this disk. The construction of Pacinotti's experimental machines is described in his original paper.

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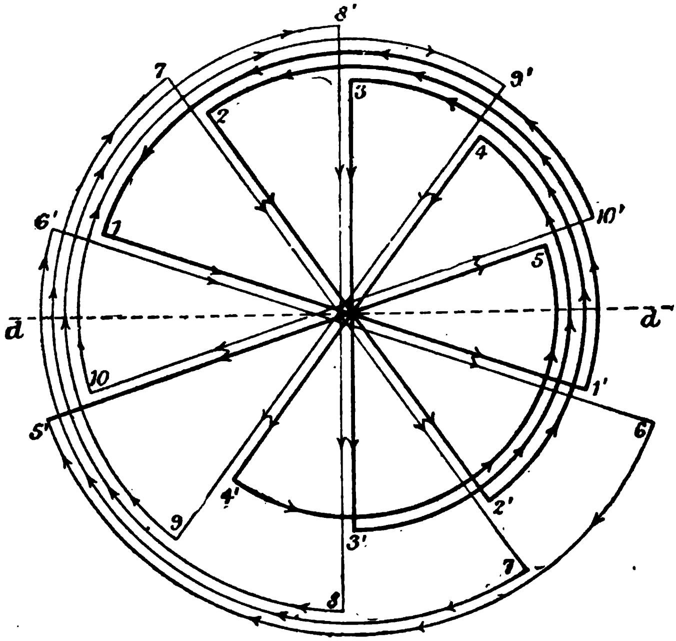
[1] *Op. citat.*

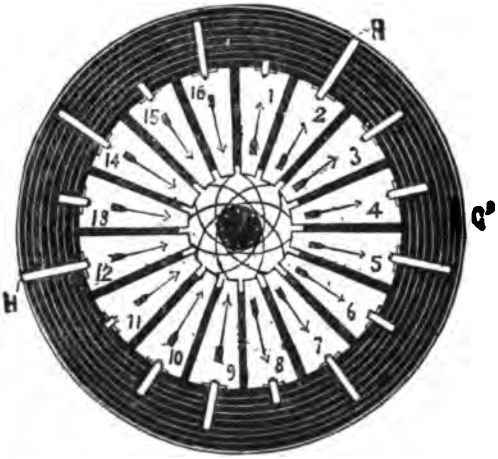
FIG. 233.



PACINOTTI'S DISK ARMATURE.

Since then many suggestions have been made for windings of this description, including the one by Edison depicted in Fig. 234.

Fig. 234.



ARMATURE OF EDISON DISK DYNAMO.

In this disk the radial plate of copper, No. 1, is connected to No. 11 by straps of copper that meet an external insulated copper rim. The spacing here is over five and eleven conductors at the same time.

A lap-winding, identical with Pacinotti's, but adapted to a 4-pole field, is depicted in Fig. 235; it is known as the Edison "new disk" winding. The disk-armatures of Hookham's electricity meters are also lap-wound. Bollman devised a multipolar disk with a wave-winding.

Recently disk-armatures have been revived by Desroziers and Fritsche. Desroziers employs for a 6-pole machine the elaborate wave-winding shown in Fig. 236. A special study of this class of winding has been made by Arnoux.[1] Fritsche employs polygonal poles, enabling him to use, as conductors, strips of metal built up in star-polygon fashion without any

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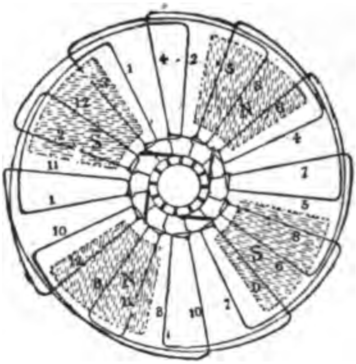
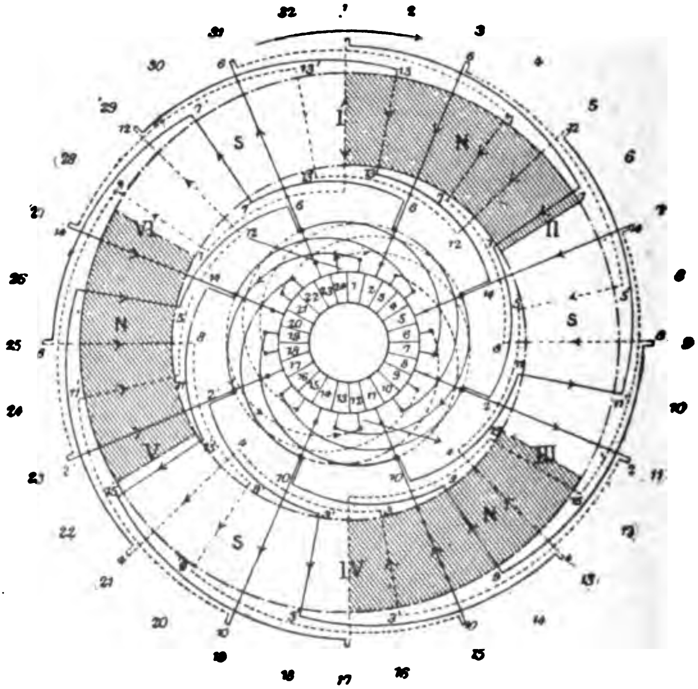
[1] See reference, p. 302.

FIG. 235.



4-POLE DISK LAP-WINDING.

FIG. 236.



DESROZIERS' 6-POLE DISK WINDING.

radial parts—a structural advantage. His disk, if developed out straight would, for a 4-pole machine, be adequately represented by Fig. 225, p. 333. The two sets of conductors constitute two layers which are united at their outer ends to the bars of a commutator at the outer periphery. The disk armature of a Fritsche machine, removed from the magnets, is shown in Fig. 36, p. 41.

CHAPTER XIII.

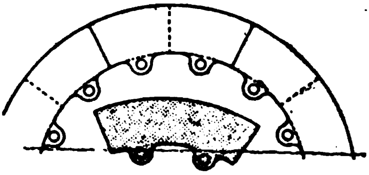
PRACTICAL CONSTRUCTION OF ARMATURES.

To carry out the proper magnetic, electric, and mechanical conditions of armature construction needs electrical knowledge, mechanical training, and experience. The mechanical problems involved have been set forth in Chapter V.; the magnetic problems in Chapter VII.; and the theory of armature-winding has been discussed in Chapter XII. In those chapters there is, however, little said about the proper modes of securing the armature-conductors, of insulating them, and of ventilating them. Most, though by no means the whole, of the present chapter relates to the armatures of direct-current dynamos and motors; but much of it is equally applicable to alternate-current machines.

Armature Cores.—Cores are always laminated, being constructed either of (1) sheet iron *disks*, (2) iron *ribbon*, or (3) iron *wire*. Ribbon is only used for discoidal armatures magnetized through the flanks. For drums and elongated rings, disks stamped out from soft sheet iron are almost universal. The usual thickness is from 1 to 2 mm. (*i. e.* from 40 to 80 mils). They should be of the softest iron, showing the least possible hysteresis. After being stamped out they should be annealed, and the burr at the edges removed. Some makers at this stage assemble them upon the shaft, turn them down truly in the lathe, then take them apart and remove the burr by grinding lightly on an emery wheel, then re-mount them. Before being finally mounted on the shaft they must be lightly insulated one from the other. For this purpose it is usual either to cover one face of each core-disk with varnished paper, or to enamel both faces of each core-disk. Mica insulation here would be too expensive, and is not necessary, as only a moderate insulation is requisite. It is usual to make the two end core-disks of stronger iron, sometimes as much as 6 mm. or ¼-inch thick. For discoidal armatures the iron ribbon must be insulated with an interposed band of varnished paper. To stiffen a discoidal armature-core it is usual to build it upon a foundation ring of soft iron, and this in some cases is constructed with a projecting central iron web, on either side of which iron ribbon is coiled. An example is afforded by the core of the Victoria (Mordey) machine, Fig. 335, p. 498.

For large machines the expense of the core-disks becomes disproportionately great owing to the waste in stamping. Hence various suggestions have been made to use segmental portions. For many years the cores of Joel's "engine-dynamos" have been built of pieces bolted together, in order to permit of the ring-windings being separately wound and slipped on. In Kapp's multipolar drum armatures (Plate IX., Fig. 2), the cores are segmental, being constructed, as shown in Fig. 237, of pieces which overlap in successive layers, each piece having eyeholes for bolts.

FIG. 237.

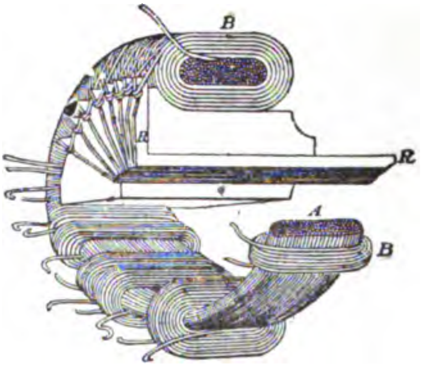


SEGMENTAL CORE-DISKS (KAPP).

Wire cores were at one time largely in vogue, having been used by Gramme. The soft iron wire, varnished or slightly oxidized on its surface, was wound on a special former, then removed, taped externally, and wound with the copper wire conductors.

Wire cores have three disadvantages. (i.) they are mechanically less satisfactory than disk cores; (ii.) they fill a given core-space with an actually less nett cross-section of iron, owing to the interstices between the separate wires, only about three-fourths of the total cross-section being occupied by iron; and (iii.) they present a discontinuity radially which offers an unnecessary reluctance in the path of the magnetic lines. The substitution of a square iron wire for a round one, as in the core of the Gülcher Company's dynamos (Fig. 339, p. 504), is an improvement in all these respects.

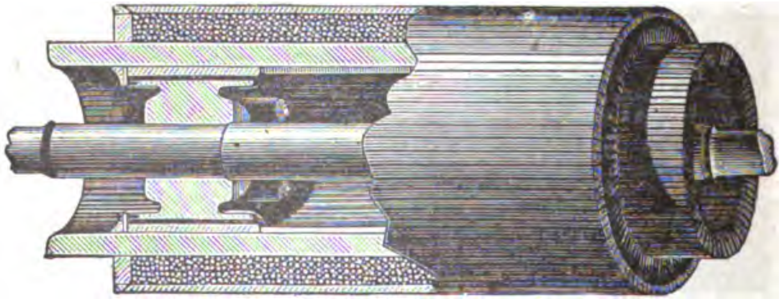
FIG. 238.



GRAMME RING WITH WIRE CORE (1871).

For machines of large output, Gramme designed the armature shown in Fig. 239. It consisted of a hollow cylinder, built up of 100 wedge-shaped copper bars, each covered with a bitu-

FIG. 239.

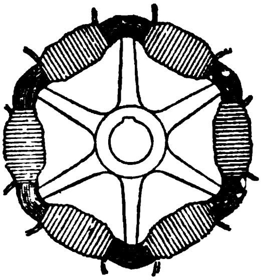


GRAMME ARMATURE FOR LARGE CURRENTS (1882).

menized paper wrapping, and then put together. Each bar had two radial projections of copper. The protruding ends of the copper rods formed the commutators, of which there were two. The space between the two sets of radial projections was filled with windings of varnished iron wire which constituted the core, and finally 100 other bars of copper of flatter section wire connected exteriorly from the projecting lug at one end of one bar to the lug at the other end of the next bar, so connecting the bars into a closed coil. Several of the inner bars were made thicker and of special form, so that they might be keyed to spiders fixed upon the driving-shaft.

Another mode of constructing wire cores is presented in the Bürgin machine. The armature of the original machine, as it came from Switzerland, consisted of several rings set side by side on one spindle, these rings being made of iron wire wound upon a square frame, and carrying each four coils. Mr. Crompton changed the square form to a hexagon having six coils upon it (Fig. 240), and increased the number of rings to ten. It was thus described in 1882:—"Each ring is made of a hexagonal coil of iron wire, mounted upon light metal spokes, which meet the corners of the hexagon. Over this hexagonal frame, six coils of covered copper wire are wound, being thickest at the six points intermediate between the spokes, thus making up the form of each ring to nearly a circle. Each of the six coils is separated from its neighbour, and each of the ten rings is fixed to the axis one-sixtieth of the circumference in advance of its neighbour, so that the sixty separate coils are in fact arranged equi-distantly (and symmetrically as viewed from the end) around the axis. There is a 60-part collector, each bar of which is connected to the end of one coil and to the beginning of the coil that is one-sixtieth in advance; that is, to the corresponding coil of the next ring. This armature has the great practical advantages of being easy in construction, light, and with plenty of ventilation."

FIG. 240.

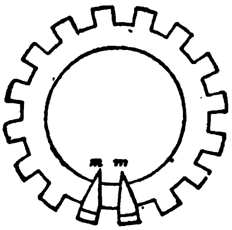


SINGLE RING FROM CROMPTON-BURGIN ARMATURE.

This form, however, suffered from the harmful effects of induction between contiguous rings, and it was found advisable to alternate the positions of the rings, instead of placing them in a regular screw-order on the spindle, as shown in most of the published drawings of this once well-known machine. It proved to be in no way superior to an ordinary Gramme armature, provided the latter was of good mechanical construction and with a sufficient cross-section of iron in the core.

Toothed and Smooth Cores.—Pacinotti's armature of 1864 (Fig. 241), was a toothed ring of solid iron supported on brass spokes, and having boxwood distance pieces fixed to the teeth to hold the windings apart. Armatures built up of toothed core-disks have been much used in recent years, particularly for motors. They have two advantages over smooth armatures. (i.) The teeth present an excellent means of driving the copper conductors which lie between them; (ii.) the teeth may be brought very close to the polar surfaces of the field-magnet, with very narrow clearance, thus bettering the magnetic circuit and therefore reducing the amount of copper required to excite the magnetic flux. To set against these real advantages are the disadvantages of somewhat greater labour required in milling out the channels between the teeth of the assembled core; the extra difficulty of insulating the core from the conductors; and the liability of the teeth to set up eddy-currents (see p. 99) in the polar faces. The latter can be cured by making the teeth numerous and narrow, also by laminating the polar faces with grooves, and by enlarging the clearance. Or, best of all, by finally serving the entire armature outside the copper conductors with a layer of iron wire. The magnetic gain in using iron teeth between the conductors is so great that sundry constructors, notably Messrs. Chamberlain & Hookham, and Messrs. Lahmeyer & Co., have built up iron projections outside smooth core-disks.

FIG. 241.

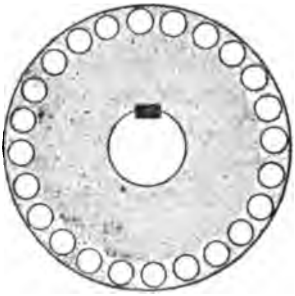


PACINOTTI'S TOOTHED-RING ARMATURE.

Examples of discoidal cores having toothed projections at the flanks are afforded by the Brush armatures, Figs. 302 and 303, p. 462.

Pierced Core-disks.—The advantages offered by toothed core-disks are possessed to a still higher degree by core-disks pierced with apertures just within the periphery. Such have been used by Wenström, by Swinburne, and by Brown. In such armatures the conductors are carried in tubes of insulating material that pass through the perforations. Brown has found this construction eminently satisfactory from the mechanical and magnetic point of view. It is used both in his drum-armature and ring-armature machines, Plates IV. and X., and Plate XXVII., Fig. 1, constructed at the Oerlikon Works. It is not however, suitable for high voltages, exceeding 100 volts or so, owing to the difficulties of insulation. One peculiar and valuable property of the pierced core-disks is, that they completely protect the embedded copper conductors however massive, from parasitical eddy-currents which would otherwise be generated in them.

FIG. 242.



PIERCED CORE-DISK.

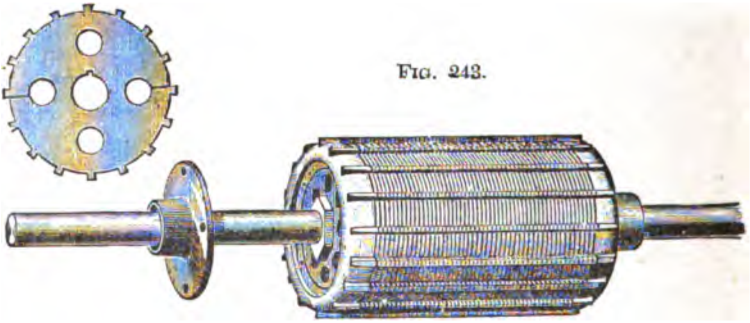
Driving Spokes and Spiders.—Armature cores are usually built up upon an internal frame or skeleton pulley firmly keyed to the shaft. In drum armatures this internal supporting frame may be omitted, the core-disks themselves being keyed directly on to the shaft. Messrs. Laurence & Scott punch hexagonal holes in the core-disks and thread them on over a hexagonal shaft.

In Weston's drum-armatures the core-disks, perforated for ventilation, are keyed to the shaft, as shown in Fig. 243.

Frequently the core-disks are held together by insulated bolts passing through them, and driven by spiders keyed to the shaft, as in Fig. 244. To this construction there is the objection that the bolt-holes reduce the effective cross-section of iron and strangle the magnetic flux. It is also needful that the bolts should be insulated from the arms of the spiders by ebonite washers and bushes, otherwise the framework will constitute a closed circuit for eddy-currents which will heat it.

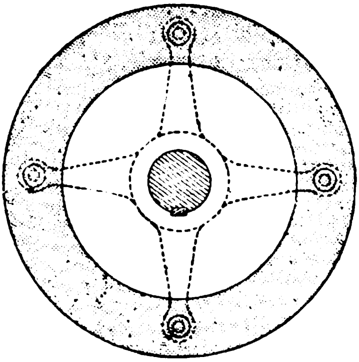
A better mode is that used by Messrs. Paterson & Cooper in their Phœnix dynamos (Fig. 331, p. 492, and Plate V.), in which the section of the iron is but slightly reduced and the bolts are entirely internal to the core. The dimensions of the machine are seen in Plate V., Fig. 2.

FIG. 243.



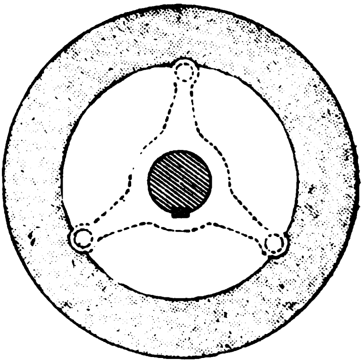
WESTON'S ARMATURE CORE AND CORE-DISK.

FIG. 244.



MODE OF DRIVING CORE-DISKS.

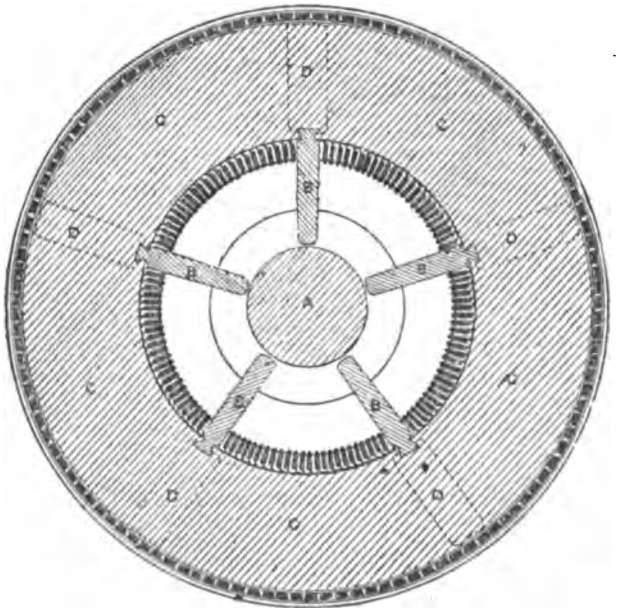
FIG. 245.



PATERSON AND COOPER'S MODE OF DRIVING CORE-DISKS.

Another mode is to provide the core disks with dovetail notches into which pass long flanges from the shaft. Mr. Crompton, in 1886, introduced this construction in the form illustrated in Fig. 246. The coils are wound upon an iron core made up of disks of very thin soft iron fixed upon a central spindle by means of short arms, which are dovetailed into notches cut in the inner circumference of the disks. At intervals gaps are left between the disks, for ventilation. The coils, ninety-six in number in some of these machines, one hundred and twenty in others, are threaded through the cylinder, and kept in their places by small boxwood wedges and by external bindings of thin brass wire. This armature is 2 feet 4 inches in length, and 12¾ inches in external diameter. The steel shaft A is grooved with five deep slits to receive five flange-like spokes B, which dovetail into notches in the iron disks C. At every 2 inches of the length there are inserted the pieces D, which are ⅛ inch thick, to

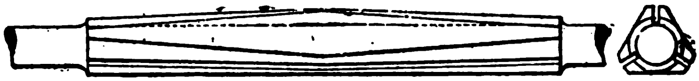
FIG. 246.



SECTION OF CROMPTON ARMATURE (1886), SHOWING DRIVING FLANGES, DOVETAILED INTO NOTCHES IN CORE-DISKS.

preserve ventilating gaps. Mr. Crompton's method of connecting with the driving shaft by grooves in the latter, is also shown in Fig. 247, which illustrates a shaft with three grooves.

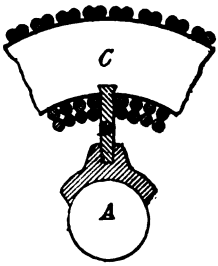
FIG. 247.



DRIVING SHAFT OF A CROMPTON DYNAMO.

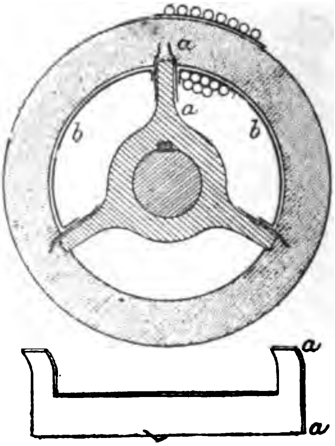
Owing to the cost of manufacture, these grooved shafts are now seldom used; a ribbed sleeve, which slips over the cylindrical shaft and is driven by a long feather, is less costly and equally mechanical. Fig. 248 illustrates a form having such a sleeve; and adapted for receiving a wire-winding in one layer externally and two layers internally. More recently Mr. Crompton makes the four projecting flanges in one solid structure instead of four separate pieces.

FIG. 248.



CROMPTON'S WIRE-WOUND ARMATURE.

FIG. 249.

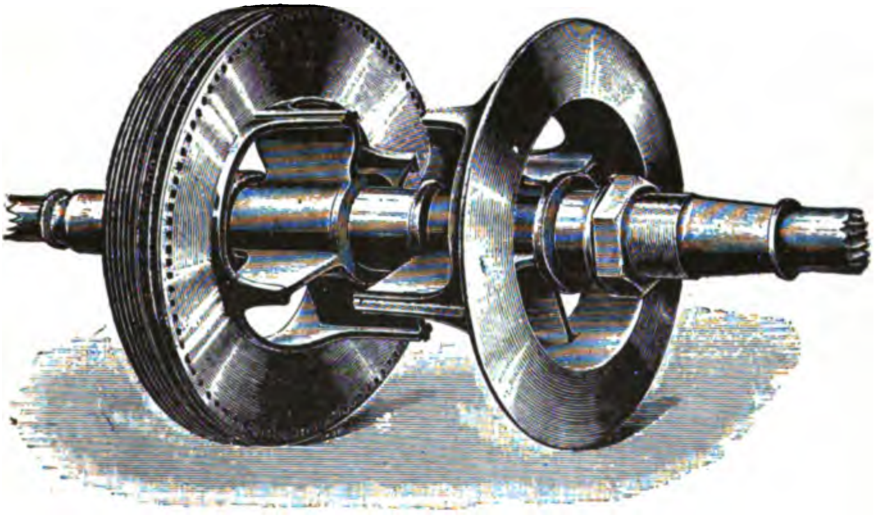


KAPP'S MODE OF DRIVING CORE-DISKS.

Kapp's mode of driving the core-disks is shown in Fig. 249, which should be compared with Plates I. and II. Over the shaft is slipped on a long sleeve provided with three projecting flanges to support the core-disks. This sleeve, which is prevented from turning by a long feather slightly sunk into a key-way, has the advantage of stiffening the shaft. In armatures for ring-winding, this internal structure is of gun-metal; in those for drum-winding, of cast iron. It is pushed up towards a face-plate which rests against a shoulder on the shaft, and the core-disks are tightened together between the two face-plates by a nut on the shaft.

Brown's mode of supporting and driving the core-disks is shown in Fig. 250.

FIG. 250.

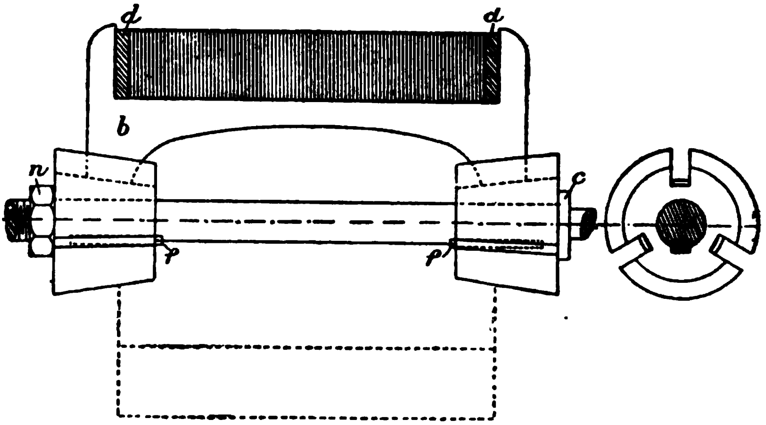


BROWN'S MODE OF DRIVING THE CORE-DISKS.

The spiders are two in number, each having four internal web-spokes and wide end-flanges. They fit over the shaft, with feathers to prevent turning. One of them is held up against a shoulder on the shaft; and after the core-disks have been assembled, the other one is pressed up by a large hexagonal nut. It will be noticed that two of the webs on each spider are ribbed; the core-disks being stamped with notches to prevent them turning. Of the four web-spokes, two are long and two short, so that the core-disks may be compressed as the spiders are forced together. Very similar arrangements for holding up the core-disks exist in Hopkinson's "Manchester" dynamos, and in Holmes's "Castle" dynamos.

Another arrangement, admirable for its strength, is employed in Immisch's motors and dynamos. Upon the shaft are placed two gun-metal cones, with shallow feathers to prevent turning. In each cone are cut three slots at angles of 120°, the bottoms of the slots also sloping cone-wise. Into these slots fit three bridge-like gun-metal flanges, with projecting lugs at their ends, to hold up the core-disks. By screwing up a nut on the shaft the cones are pressed together, and thereby the three flange-spokes are forced outwards and support the core-disks at three points of their internal periphery. Coned devices resembling more or less this highly mechanical arrangement, are to be found in some forms of ring armatures designed by Spang, and in others, designed by Raffard. In the case of the Immisch machines

FIG. 251.



IMMISCH'S METHOD OF DRIVING BY TWO CONES.

the core-disks are neither notched nor keyed; but at the ends, and at intervals, thicker iron disks are inserted with projecting driving horns.

It should not be forgotten that compressing stresses diminish the magnetic permeability of iron in the direction of the stress; and that tensile stresses increase the permeability.

Insulation of Iron Cores.—Mention has been made of the proper mode of insulating the core-disks internally from one another by interposing paper or enamel. Theoretically there is no need to insulate them from the shaft in those cases where they are threaded on directly; it is at their peripheries mainly that they must be prevented from making metallic contacts with one another. But beside this internal insulation, they must be protected very carefully from *external* contact with the copper conductors. It is usual to serve the completed core with one or two coats of enamel or japan, and then to cover it with a layer of some tough material such as canvas, manilla-paper, or Willesden-paper, well varnished with shellac varnish or with Scott's rubber varnish. In the case of cores for ring-winding, particular care must be taken to insulate the inner periphery and the driving spokes, where the internal windings lie near them. In the case of drum cores the ends must be well protected, and those portions of the shaft that are close to the ends. In Kapp's ring armatures, pieces of thin vulcanized fibre, of the form shown in Fig. 249, p. 350, are inserted on each side of the driving flanges, and other pieces are coiled around the internal periphery between the flanges in the manner shown. The mode of insulating the cores of Brush rings is described on p. 455.

Ventilation of Armatures.—Armature cores heat from three causes: hysteresis; eddy currents; and heat derived from the copper conductors. The careful lamination and insulation described above, are but means to prevent waste of power and to avoid risk of overheating. In the case of ring-wound machines there is usually an amount of surface exposed sufficient to get rid of the heat generated in the conductors without resorting to any special mode of ventilating. But in the case of large and solidly constructed drum-armatures, some mode of forcing the ventilation may be necessary. In drum-armatures with the old-fashioned wire-windings overlapping the ends, adequate ventilation is impossible. As examples of ventilated cores the reader should see Crompton's armature, Fig. 246, p. 349; Kapp's drum armature, Plate II., Fig. 1.

In the case of drum-windings having end connexions built up, the arrangements with one set of evolute spirals and one set of straight radial pieces (as in Fig. 212, p 322) are preferable to those with two sets of spirals as in Fig. 214, p. 323, since the former have a better fan action. Some makers use spiders with arms sloped like the sails of a windmill, so as to propel air through the interior of the armature.

Balancing of Armatures.—It is very needful that armatures should be properly balanced, otherwise they will set up injurious vibrations in running. Most makers test their armatures for balance by laying the journals on two parallel metal rails (or "knife-edges") and noting whether the armature will remain in any position without tending to roll. It is well indeed to balance them thus on completing the core ready for winding, and again after winding. If the end core-disks have been made of thick iron, holes can be drilled in these to restore perfect balance: or leaden plugs can be inserted.

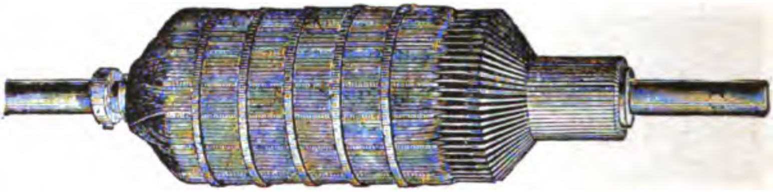
It may be remarked that this mode of observing the statical balance is not perfect; for if the masses that balance around the axis are distributed unsymmetrically along the axis, there will be, when running, a tendency to spin around the axis of maximum moment of inertia, which will set up a vibration.

Driving Horns.—It is of primary importance that the armature conductors should be properly driven, otherwise they may be raked out of place by the tangential drag in the magnetic field (p. 111). In the case of ring-windings, such injurious action is less likely to occur than with drum-windings, as the convolutions which thread through the interior of the core tend to bind, and press against the driving spokes. But even here, it is found needful to provide positive driving at a number of points around the periphery. Crompton found it needful to drive boxwood wedges in between the core-disks. He then adopted the construction of Fig. 246, p. 349, in which the pieces of fibre D are inserted at intervals for ventilation between the core-disks; the gaps so left being convenient for the insertion of driving horns between the wires. Kapp uses projecting narrow steel horns protected by pieces of hard fibre. Goolden uses strips of hard white fibre inserted into shallow keyways milled out of the surface of the core; there being usually 24 short fibre keys, inserted in 8 rows of 3 each, the rows being 45° apart. They are held in by the external binding wires. For discoidal armatures the driving horns must project at the flanks, being inserted between the core ribbons.

Binding Wires.—After an armature has been wound the conductors must be secured in their place by a number of external bands, known as *binding wires.* These must be very strong, to resist centrifugal force and to hold the conductors from being dragged aside; and yet at the same time must occupy very little radial depth, that the clearance between conductors and pole-face may be as narrow as possible. Some makers use hard-drawn brass, others phosphor-bronze, others steel, for binding wires. The almost invariable practice is to employ a tinned wire, which, after winding, can be sweated together with solder into a continuous band. It is impossible to give rules for the sizes of binding wires. A frequent size for steel wire is 40 mils, or a little under 1 mm. diameter. The wire is wound on in bands of from 10 to 30 turns each; the separate bands being spaced out at distances of from 1 to 2 inches apart. Under each belt of binding wires a band of insulation must be laid. This usually consists of two layers; first a strip of thin vulcanized fibre slightly wider than the band of wires, and then a strip of mica (in short pieces) of about equal width. Some makers lay a small strap of thin brass under each band of binding wires, having ends which can be turned over and soldered down to secure the two ends of the wire from flying out. Fig. 252 depicts a completed drum-armature of Weston's pattern (compare Fig. 243, p. 348) showing five bands of binding wires.

Mr. Esson states that Messrs. Paterson and Cooper use three sizes of piano steel wire, namely 18 mils, 20 mils, and 26 mils, respectively, in diameter. On a drum armature 10 inches in diameter and 12 inches in length he would place six bands of 18-mil (*i. e.* No. 26 B.W.G.) wire, each band being about ⅝ inch wide and containing about thirty-three turns; the bands being, therefore, rather less than 1½ inches apart. On a drum or ring 20 inches in diameter he would use 35-mil wire, in bands ½ inch wide, about 2 inches apart.

Fig. 252.



Completed Drum Armature (Weston's Pattern).

Winding Armatures.—Given a scheme of winding according to any of the modes discussed in Chapter XII., the problem remains how to carry it out in the factory. Ring-windings may be considered first, then drum-windings. Disk-windings, as carried out by Desroziers and by Fritsche, are sufficiently discussed on p. 337. A broad distinction may be set up between wire-wound armatures and those with built-up coils consisting of bars and connectors, or of specially constructed portions that are put together instead of being wound on. Wire-wound armatures are usual for outputs below 100 amperes, including all arc-lighting machines. For armatures having outputs exceeding 200 amperes bar-armatures are more frequent, owing to the inflexible nature of wires that are thick enough to carry these currents. The two classes comprise several varieties as under:—

WIRE-WOUND ARMATURES.	BAR ARMATURES.
Single round wire.	Round bars.
Two or more round wires in parallel.	Rectangular bars.
Stranded wire.	Imbricated rectangular strips.
Single square wire.	Rectangular bars of compressed stranded wire.
Single rectangular wire.	Special forgings.
Laminated strip conductor.	

Single round wire, insulated with double cotton covering soaked afterwards with shellac varnish, is usually adopted for small machines and arc-lighting dynamos. Messrs. Goolden & Co. use silk-covered wire. For small electroplating dynamos it is frequent to use several round wires in parallel, even to as many as twenty or thirty separate wires side by side. Wire-drawers will furnish rectangular wire of any desired section; but, for greater flexibility in winding, a rectangular conductor made of three or four separate strips laid side by side, and then served with a coating of tape to hold them together is preferable, and has been for some years used in Holmes's dynamos. It has the advantage of partially eliminating eddy-currents in the conductors themselves.

For bar-armatures rectangular bars set edge-ways to the core are more frequent than round bars; but armatures in which solid bars are used are liable to a serious waste of work that does not occur with wire-wound armatures. When the conductors present a considerable breadth, eddy-currents are set up in them as they enter or leave the magnetic field, owing to the fact that one edge of the bar may be passing through a field the intensity of which is very different from that of the field through which the other edge of the same bar is passing. Assuming a peripheral speed of 1700 to 1800 feet per second, it is found in practice impossible by any shaping of the pole corners to avoid excessive heating of solid copper bars on the armature if their breadth exceeds 5 mm. The work wasted in producing these eddy-currents may even reduce the efficiency of the dynamo by more than 5 per cent. This does not, however, occur in those armatures in which the bars are sunk deeply between teeth, or pass through holes in the core-disks. To reduce such losses, bars made of several strips oxidized on the surface, or lightly insulated by oiling or enamelling, and united only at their ends, have been used. Crompton[1] has proposed several modes of twisting or imbricating around one another two or more strips, so as more effectually to neutralize the eddy-currents. More recently he and other makers have used bars made of stranded copper wire compressed into a rectangular form, each wire being oxidized or lightly insulated.

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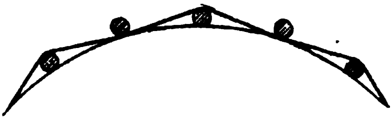
[1] See *Journal Institution Electrical Engineers*, xix. 240, 1890.

Yet another mode of armature construction, described later, consists in winding the insulated wires or strips upon special formers or moulds, in groups which are afterwards laid on or around the armature core. One advantage in such methods is the greater ease of securing perfect insulation between those parts of the windings which differ greatly from one another in potential. In drum-windings, if the conductors lie in one layer, there is an extreme difference of potential between each conductor and its next neighbour. Whereas if they lie in two layers, an intermediate sheet of insulating material can be laid between. It has also been suggested that in one-layer windings an insulating sheet may be introduced, as in Fig. 253, to keep the two sets of conductors apart.

FIG. 253.



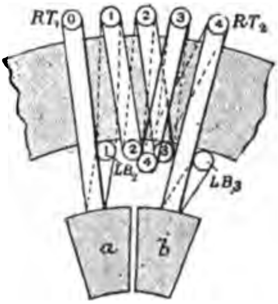
INSULATION OF ALTERNATE WINDINGS.

Wire-wound armatures are usually well served with shellac varnish or india-rubber solution after the winding is completed. They should be well dried in a stove at steam-heat after varnishing.

Modes of Winding Ring Cores.—When a ring core is to be wound it is frequent to stencil upon the end faces a number of radial lines corresponding in breadth to the separate sections so as to guide the winder in his work.

For ring-windings there is, in general, little trouble. Nevertheless some care must be exercised. The separate "sections" of the coil are almost invariably wound on the cores separately, leaving the ends projecting, secured temporarily with string, and these ends subsequently connected together and to the commutator. An inexperienced workman may easily connect up wrongly; making a left-handed winding instead of a right-handed one, or *vice versâ*. Hence it is well to provide him with some such working drawing as Fig. 254, which relates to a right-handed winding having four turns in each section. The wire marked "o" is the last or outer end of the section previous to that considered. This end will eventually be brought down to a bar *a* of the commutator, and from this bar will go out the beginning or left-bottom end, marked L B, of the section in question. Looking at this diagram the winder will see that the wire L B must pass under the core to the far end and then return over the top, thus making turn No. 1. It will then bend down to the right, be threaded through again, and make turn No. 2; again, and make turn No. 3; but as the inner space is narrower than the outer space, turn No. 4 will probably have to ride on, or partly bed between, the turns already wound. The right-top end, marked R T, will eventually be joined to bar *b* of the commutator. If the winder is shown that the right-top wire of one section joins the left-bottom turn of the next section at the commutator, he will have no excuse for mistakes. The winding of multipolar rings is absolutely similar, provided as many brushes are applied to the commutator as there are poles.

Fig. 254.

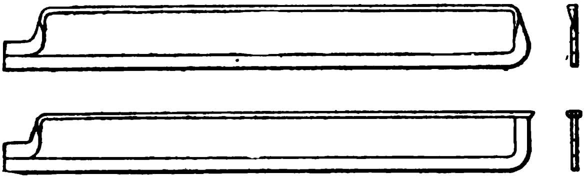


Winding Diagram. Ring Armature.

For arc-lighting armatures, and in general those which have numerous convolutions of wire to each section, it is convenient to prepare the wire in separate lengths sufficient for each section, and to coil each length on small shuttles each length being wound upon two shuttles, which are alternately used for successive layers. By this device both ends of the wire that constitutes a section are brought to the outside instead of one of them leading directly down to the bottom layer, as in ordinary bobbin winding.

For those machines that only require one, or two, complete turns to each section, it is common to have the copper conductors prepared beforehand upon separate formers, and ready taped to be slipped on over the cores. Crompton introduced the forms illustrated in Fig. 255, consisting of drawn copper of nearly rectangular section twisted at the ends so as to pack closely in the interior of the ring. These conductors are sprung on over the ring core, with appropriate insulation between them, and afterwards coupled up so as to make a continuous winding.

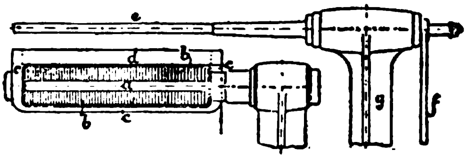
FIG. 255.



WINDINGS OF CROMPTON'S ARMATURES (1886).

In the large multipolar ring dynamos with internal field-magnet and external commutator, now so much used for central stations in Germany, the windings are so constructed that their outer part serves also as commutator, as in Plate XI., Fig. 3. The ring consists of core-disks built up of segmental plates, shown in section at *b*, Fig. 256, supported by driving-rods *a* which pass through them. After being covered with suitable insulation, the copper conductors *c d* are slipped on over them, and coupled up to make a continuous spiral winding. The insulation between, as used by Siemens and Halske who introduced this type, is a preparation of paper. The outer part *d* of the copper conductor is made both deep

FIG. 256.



CONSTRUCTION OF GERMAN MULTIPOLAR RING ARMATURE.

and broad, and serves as a commutator bar. The brushes (not shown) are fixed upon the projecting bar *e*, and trail on the outer periphery of the copper windings of the ring. At *f* is a lever for raising the brushes out of contact.

Drum winding.—Drum armatures of all types may all be regarded as modifications of Siemens' well-known longitudinal shuttle-form armature of 1856, a multiplicity of sections of the coils being employed to afford practical continuity in the currents. The drum pattern was invented in 1872 by von Hefner Alteneck, of the firm of Siemens and Halske, of Berlin. In this system, as in the Gramme ring, the successive "sections" or groups of coils that are wound on the core, are connected together continuously, the end of one section and the beginning of the next being both united to one bar of the commutator. It is important to note the difference between this and the ring winding. In a ring winding the volts induced in any one section (at a given speed) depend only on the magnetic field at one side of the armature; but in a drum winding the volts induced in any one section depend on the two magnetic fields at the two sides, since each winding wraps over the drum nearly diametrically. As a result, drum-wound armatures are less liable to spark; and they possess a smaller self-induction than ring windings.

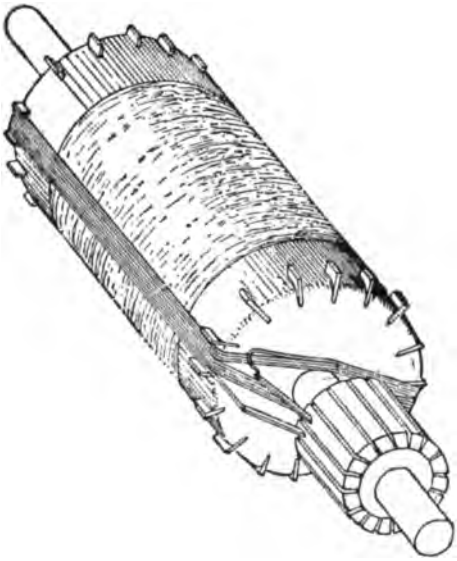
The advantages of the drum form of armature appear to be (1) that they require somewhat less wire than the ring armature of equal size; (2) are free from liability to false inductions, (p. 433), and therefore more independent of the form of the pole-pieces; (3) have smaller cross-magnetizing tendency than ring armatures. Their disadvantages hitherto have been: (1) greater difficulty of construction; (2) greater difficulty of securing proper insulation on account of overwrapping of conductors; (3) greater difficulty of ventilation; (4) greater difficulty of executing repairs.

Siemens' Dynamo.—In some of the earlier patterns of Siemens' machines the cores of the drum were of wood, overspun with iron wire circumferentially before receiving the longitudinal windings. In another of their machines there was a stationary iron core, outside which the hollow drum revolved; in other machines, again, there was no iron in the armature beyond the driving-spindle. The process of constructing the armature employed down to the year 1885 is shown in Fig. 257. Upon the axle are secured by pins two stout cheeks of gun-metal to form the ends of the drum. Between these, and resting on an inner projecting rim, is wrapped a thin sheet of iron, and over this a quantity of soft iron wire is wound to form a core, as in the Gramme armature. A number of cuts, equal to the proposed number of segments, are sawn radially in the end faces of the gun-metal cheeks, and in these cuts small boxwood wedges are inserted to facilitate the winding. The coiling of the sections is done in the following manner:—The wire is carried along the drum, as shown, four of the strands passing to the left, four to the right of the axle at either end, and is then ready to be turned over to meet the connecting piece of the second segment of the commutator. From this point the next section will start in a like manner; but before the second section is wound the drum is turned completely over, and the section diametrically opposite to section No. 1 is wound on the top of the eight strands already wound. Thus, in a 16-part armature, section No. 9 lies on the top of section No. 1, No. 10 on the top of No. 2, and so on, there being two layers of coils all over the drum. The two layers must be thoroughly insulated from one another, to ensure that parts which are at very different potentials shall never come in contact with one another. Although, for the sake of rendering the connexions more intelligible, the commutator is shown in Fig. 257 in its place on the axle, it is not, as a matter of fact, put into its place until after all the sections have been wound, the ends of the wires being temporarily twisted together until all can be soldered to the connecting strips of copper. In some of the armatures intended for electro-plating machines there are four layers of wire, and the wires are connected together four or eight in parallel to reduce the resistance.

So far all is simple, but when we pass on to the construction of bar armatures, new complications arise.

To connect the conductors of a bar armature across the ends of a drum is not so simple a matter as might at first appear. Suppose that a scheme of connexions has been worked out beforehand in one of the ways described in Chapter XII., and that a winding-table has been prepared in which the order of the end connexions is set down. It yet remains to determine the mechanical devices for the end connexions which shall be compatible with working conditions. The end connectors must be good conductors, sufficiently well insulated from one another, allowing of repairs and ventilation, and mechanically sound. Wire-wound drums present an ugly over-wrapping at the ends, which stops ventilation and hinders repairs. Quite early, Messrs. Siemens devised, for their electro-plating machines, a system of uniting by spiral connectors the ends of the copper bars. To connect any bar with that lying next to the one diametrically opposite, two spiral strips of copper were applied, one bending inwardly, the other outwardly, their junction being mechanically secured to a block of wood on the shaft. Their outer ends were attached

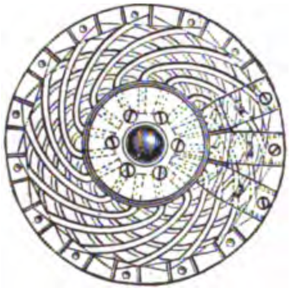
FIG. 257.



METHOD OF WINDING SIEMENS' ARMATURE.

to the bars by silver solder. At each end of the drum these spiral connectors constituted two separate layers. These systems of spirals, with more or less modification, are to be found in the majority of recent drum armatures.

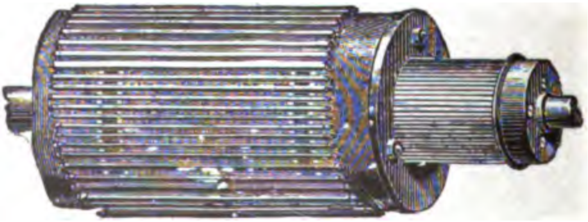
Fig. 258.



Siemens Bar Armature.

In Edison's modification of the drum armature, the winding, though symmetrical in one sense, is singular, inasmuch as the number of sections is an odd number. In the first machines there were seven paths, as shown in Fig. 208, p. 319, taken from Edison's British Patent Specification. In his giant "steam dynamo" (1883) the number of sections was forty-nine. One consequence of this peculiarity of structure is, that if the brushes are set diametrically opposite to one another, one will touch the middle of a bar of the commutator at the instant when the other slides from bar to bar. In Edison's larger dynamos, the armature is constructed of solid bars of copper, arranged round the periphery of a core consisting of thin iron disks separated by mica or paper. Fig. 259 shows the armature removed from the machine. The ends of the bars are connected across by washers or disks of copper, insulated from each other, and having projecting lugs, to which the copper bars are attached. Such disks present much

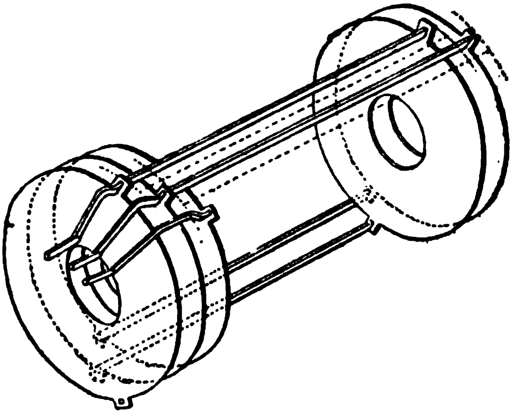
Fig. 259.



Armature of Edison Dynamo.

less resistance than mere strips would do. To make the mode of connexion plainer the diagrammatic sketch of Fig. 260 is given. The connexions are in the following order:—Each of the forty-nine segments of the commutator is connected to a corresponding one of the forty-nine disks at the anterior end of the drum; and this disk is connected, by a lug-piece on one side, to one of the ninety-eight copper bars. The current generated in this bar—say, for example, the highest of the three bars shown in Fig. 260—runs to the farther end of the machine, enters a disk at that end, crosses

FIG. 260.

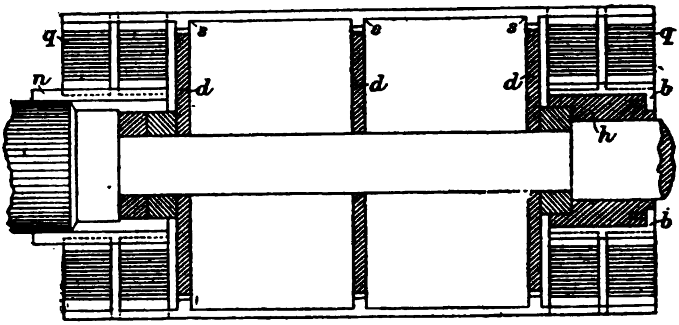


CONNEXIONS OF EDISON ARMATURE.

the disk, and returns along a bar diametrically opposite that along which it started. The anterior end of this bar is attached to a lug-piece of the next disk but one to that from which we began to trace the connexions: it crosses this disk to the bar next but one to that first considered, and so round again. The two lug-pieces of the individual disks at the anterior end are, therefore, not exactly opposite each other diametrically, as the connexions advance through $\frac{1}{49}$ of the circumference at each of the forty-nine paths. To simplify matters, in the drawing the alternate disks and bars are only indicated in dotted lines. Just as the two bars shown at the bottom are the returns for the currents in the top bars, so there must be top bars provided as returns for the currents in those bars (not shown) which start from the segments of the lower half of the collector. The dotted lines show the position of these return bars. The construction is mechanically excellent, but it does not admit of ventilation ; and the stray field at the ends of the armature is liable to set up eddy-currents in the substance of the copper disks.

In the Edison-Hopkinson armatures built by Mather and Platt, Edison's device has been abandoned in favour of a system of spiral conductors, as already described on p. 363. The construction of Hopkinson's armature, as carried out for a machine in which there is one convolution in each section of the winding, is indicated in Fig. 261.

FIG. 261.



SECTION OF HOPKINSON'S DRUM ARMATURE.

The core, which is built against a shoulder on the shaft, consists of numerous disks of thin iron, but with a few thicker core-disks, *d*, *d*, interposed at the ends and at intervals between. These are clamped up by nuts at the end near the commutator C. The conductors of copper are provided with driving lugs *s s*, which, properly insulated, project into notches cut in the thick core-disk. The systems of spiral connectors are shown in section at *q q*. At the commutator end they join the conductors down to a set of copper pieces *n*, which run to the corresponding bars of the commutator. At the other end, the spirals are inserted into a set of copper pieces *b* assembled around a wooden hub *h* by which they are driven, being screwed in through end lugs. For armatures in which each section consists of two convolutions, it is necessary to provide four layers of spiral connectors at each end.

Many successive modes of drum connexion have been tried by Mr. Crompton. In conjunction with Mr. Swinburne he devised a method of connecting the conductors of a drum armature which enables the core to be ventilated. The fundamental point in this construction is illustrated by the simple form sketched in Figs. 262 and 263. There is only one layer of conductors outside the core, and these consist of copper wire of narrow rectangular section set edgeways. Every alternate conductor of the set is bent radially inwards for a certain distance, and then recurved outside again parallel to the axis of the drum. The conductors that lie between them are prolonged straight outwards to a certain length. The result of this arrangement is that there are two concentric sets of projecting ends. Connexion is made by a spirally-bent strap of copper from the ends of one of the outer straight set to one of the inner recurved set; for example,

FIG. 262. FIG. 263.

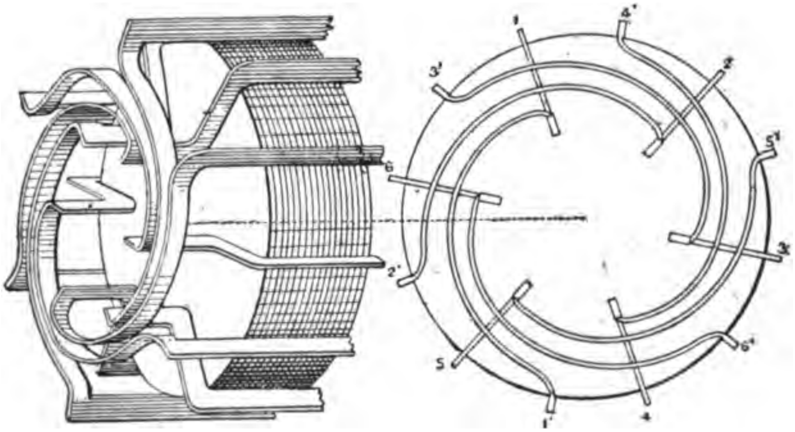
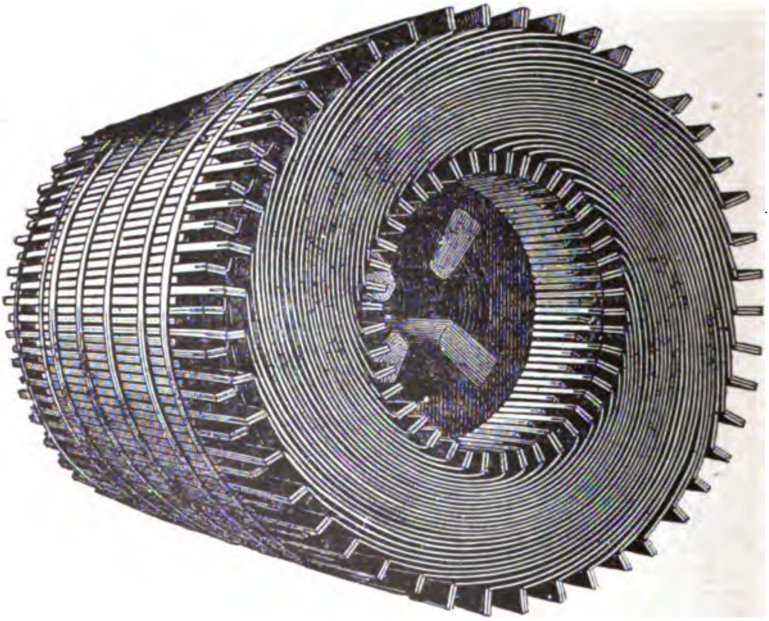


DIAGRAM OF CROMPTON AND SWINBURNE'S METHOD OF DRUM WINDING.

to the one that lies next to that at the diametrically opposite point of the periphery. In Figs. 262 and 263, which depict the connexions at one end of a simple six-part armature (the six-part commutator at the other end is not shown), conductor 1 is connected in this manner to conductor 1′. At the other end of conductor 1′ (not shown) there would be a similar cross-connexion to the far end of conductor 2; and the near end of 2 is joined to 2′; and so forth. Or the same method of connecting by spiral straps may be applied to winding across a shorter cord, as on Swinburne's plan of chord winding (p. 304). The method of connecting by spirals of copper differs from that adopted in the Siemens electroplating dynamos, Fig. 258, p. 364, in the use of the cranked pieces. In the actual construction of large drum armatures the Crompton and Swinburne construction is more complex,

FIG. 264.



CROMPTON AND SWINBURNE'S DRUM ARMATURE.

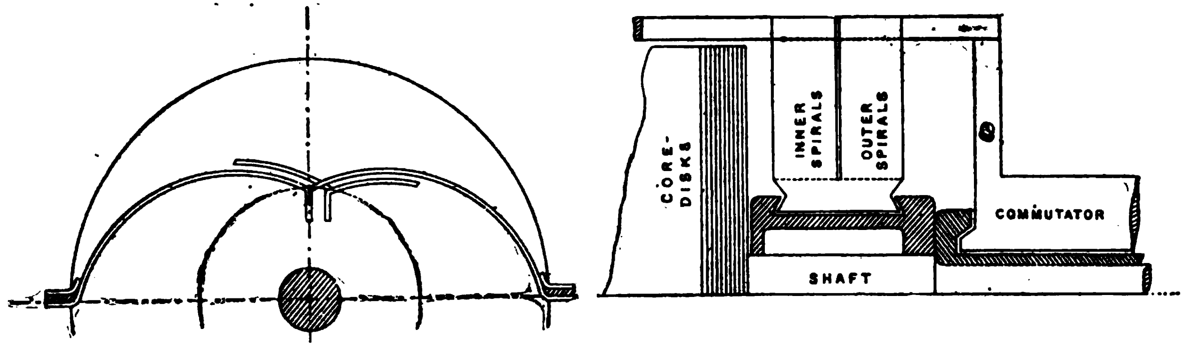
as it is impossible with a very large number of conductors to find room for all the spiral connectors in one whirl. Accordingly, there are two separate layers of spiral conductors, the projecting extremities of the conductors at the ends of the drum being themselves made alternately long and short, the short projections being connected by one layer of spirals, and the long projections being connected by another layer of spirals. The armature as so constructed is depicted in Fig. 264. The difficulty of getting at the inner spirals in this construction led to another suggestion by Crompton and Kyle, namely, turn the spiral connectors outward instead of inward, at the ends of the drum, which thus becomes enlarged in diameter.

The present modes used by Crompton for drum armatures are sketched in Figs. 265 and 266.

In the first of these, which is for a 2-pole dynamo, the spiral connectors, stamped out of sheet copper, are driven by mechanical attachment to a clamping sleeve keyed to the shaft. In the second, which is for a 4-pole machine, the spiral connectors, being shorter, do not require to be similarly tongued. The conductors are made of stranded wire compressed to rectangular section.

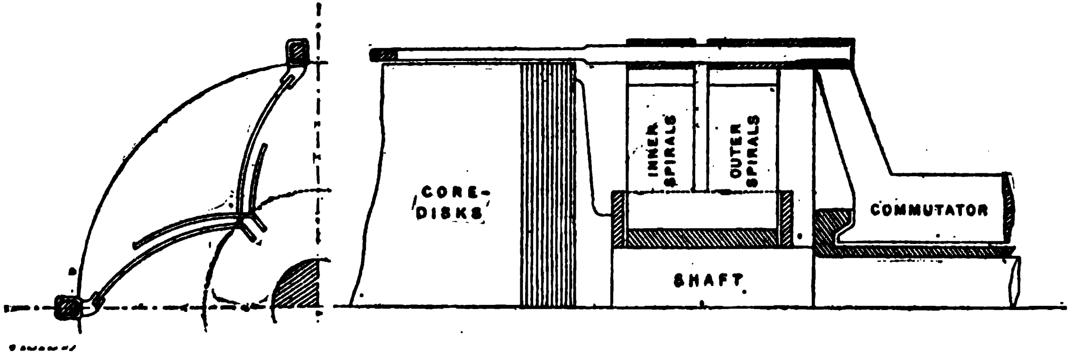
A method based on that of Paris and Scott is used by Kapp both for bipolar and multipolar drums. The connectors are stamped out from this sheet copper in the form of semicircular or quadrantal arcs, provided with lugs (as shown on Plate II., Fig. 2) which can be bent, one forward, one backward, thus enabling connexions to be made by a whole series of such connectors arranged skew-wise, with suitable insulation between, in a carriage or bobbin mounted on the shaft. The connectors are assembled together to the proper number, and held in with binding wires in the channel of this carriage, which is then put in place, and the lugs are soldered into grŏoves cut in the ends of the armature conductors, which for this purpose are made alternately long and short at their ends. The best way to understand this method is to make a few model connectors in paper or cardboard, and lay them over one another.

FIG. 265.



CROMPTON DRUM WINDING FOR CENTRAL STATION MACHINE, 2-POLE DYNAMO.

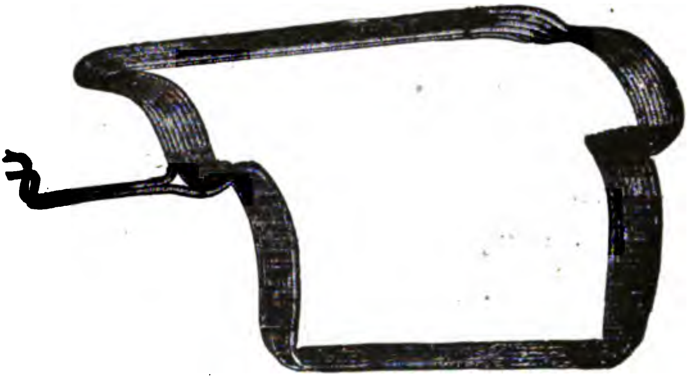
FIG. 266.



CROMPTON DRUM WINDING FOR LARGE OUTPUT 4-POLE DYNAMO (PARALLEL CONNEXIONS), 4 SETS OF BRUSHES.

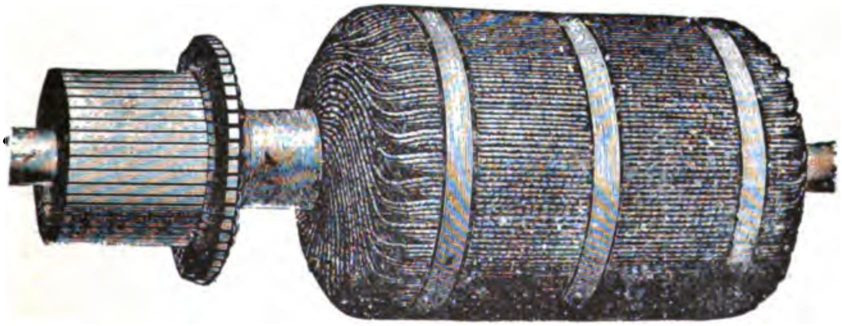
Eickemeyer's mode of construction differs from the preceding, in being applicable both to wire-wound drums and to strip-wound drums. In it, each section, whether consisting of many convolutions or of only one, is first shaped upon a separate former, and each such section is separately insulated. Fig. 267 shows the form given to the sections. The lower part will form part of an inner layer, and the upper part, which is longer, will form part of an outer layer in the assembled windings. The completed armature, with its binding wires, is shown in Fig. 268. The narrow neck between

FIG. 267.



SEPARATE SECTION OF EICKEMEYER'S ARMATURE.

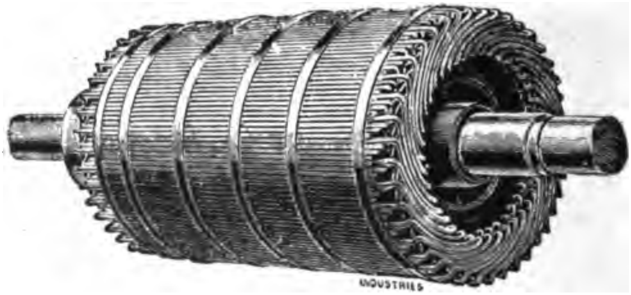
FIG. 268.



EICKEMEYER'S ARMATURE, COMPLETE.

the drum and the commutator is necessitated by the form of field-magnet (Fig. 128, p. 203) adopted in this machine. The Eickemeyer winding has also been adopted by the Edison Company[1] in its recent machines.

FIG. 269.



ALIOTH'S DRUM ARMATURE.

Fig. 269 depicts a drum armature by Alioth, of Basel, having four layers of spirals at each end, designed for a 4-pole field.

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[1] See *Electrical World*, xvi. 249, 1890.

CHAPTER XIV.

COMMUTATORS, BRUSHES, AND BRUSH-HOLDERS.

DYNAMOS for furnishing direct currents require a *commutator* (sometimes called a *collector*) and *brushes* to collect the current. The essential action of these organs has been already described (see pp. 39 and 84); and the causes that give rise to sparks are discussed in Chapter IV., p. 83, and in Chapter XVI. We have now to consider the design and construction of these organs.

We may distinguish three types of apparatus for collecting the currents from dynamo-machines.

I. Direct-current dynamos with closed-coil armatures, as used for incandescent lighting and other work requiring a constant or nearly constant potential, are furnished with a commutator of the Pacinotti type, that is to say consisting of a considerable number of parallel bars secured around an insulating hub, and presenting a cylindrical surface, against which press a pair (or in some cases more than one pair) of brushes or sets of brushes.

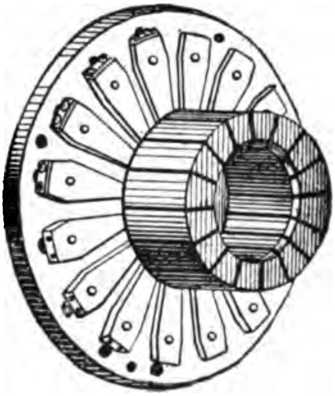
II. Direct-current dynamos of the open-coil type, as used for arc lighting, and giving a constant or nearly constant current, are provided with a commutator consisting of a comparatively small number of segments, each covering a considerable angle, and separated by air-gaps from one another. These are described in Chapter XVII.

III. Alternators with revolving armatures need a pair of collecting rings of metal, each provided with one or more brushes, or some analogous device to form a sliding connexion with the circuit. Alternators with revolving field-magnets need a similar device to convey the exciting current to the moving coils. These devices are considered at the end of the present Chapter, which is in the main devoted to apparatus of the first of the three classes enumerated.

Commutator Bars.—The number of bars of the commutator depends on the scheme of winding and on the number of sections in which the armature winding is grouped. Increasing the number of bars diminishes the tendency to spark (p. 87); and lessens the fluctuations of the current, (p. 221). An even number of bars is preferable to an odd number; and for ring-wound armatures the cores of which are usually carried on three-armed spiders, it is preferable that the number of bars should be a multiple of three. There are however, two practical reasons against making the number of bars very great. Increasing the number increases the cost. Again, in large machines having but one turn of the armature winding from each bar of the armature to the next, the number cannot be greatly increased without exceeding the voltage desired. For example, in an Edison-Hopkinson machine for an output of 1100 amperes at 105 volts, only 43 convolutions are required. On the other hand, it is found for small dynamos, that if the number of bars is increased, each bar becomes so thin that a brush of the proper thickness to collect the current would bridge more than two commutator bars at once. Again, the bars should be of a length proportioned to the number of amperes that is to be taken off at them. Modern practice varies somewhat, but it may be fairly represented by some such figure as 1·2 inches for every 100 amperes. The mode of attachment of the bars should be such as to make the greatest amount of length available. They should also be of considerable radial depth, to allow for wear, as the commutator needs to be turned down from time to time to preserve cylindricity. As for the material most makers use hard-drawn copper, made in long lengths of the proper section, and cut off to the length required. Some American makers use drop-forgings of copper, stamped to shape with projections for clamping and connecting to the windings. Crompton has used phosphor bronze, but now casts a special alloy of copper containing a very small percentage of silver.

Insulation.—It is needful to have a good insulation between each bar and its neighbours, and a specially good insulation between the bars and the sleeve or hub around which they are mounted, and also between the bars and the clamping devices that hold them; for the difference of potential is small between neighbouring bars, and much larger between the bars and other metal-work. The insulating material must not absorb oil or moisture: hence asbestos and plaster are inadmissible. Vulcanized fibre and Willesden paper are not by themselves adequate, though mechanically strong. Mica is the only satisfactory material. Commutators with air-gaps between the bars have been used by Ayrton and Perry, by Hochhausen, and by Siemens and Halske (p. 508). In Hochhausen's machine the commutator (Fig. 270) consisted of L-shaped bars bolted to a disk of slate. The trouble with air-insulation is to keep the gaps from being filled by metallic dust from the wearing of the brushes.

Fig. 270.

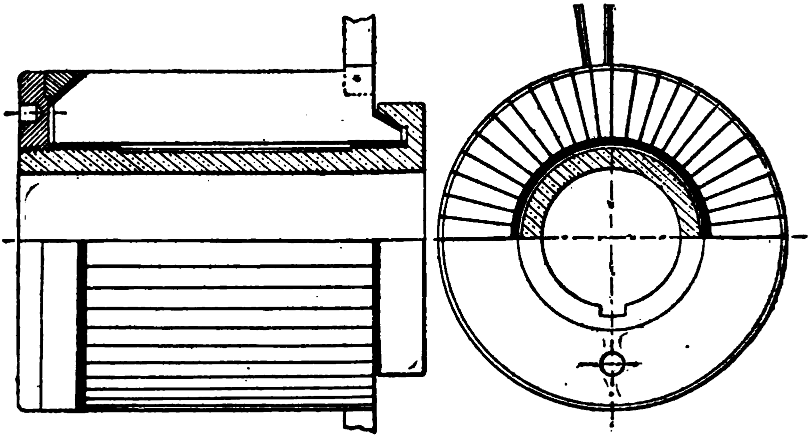


Commutator of Hochhausen Dynamo.

Construction of Commutators.—Fig. 271 shows the construction adopted by Messrs. Paterson and Cooper. The bars are clamped in place by fitting at one end into a groove in a gun-metal sleeve, and at the other by an external clamping ring which is forced over their bevelled ends by a large screw-washer. The insulation is carried out by thin slips of mica between the bars, and layers of mica and vulcanized fibre around the sleeve and clamping surfaces. The clamping ring in this case reduces the available surface for the brushes.

In the Gülcher Co.'s machines a construction is adopted which is illustrated by Figs. 272 and 273, and of which a section is given in Fig. 274. The drawings relate to a 4-pole machine with only two sets of collecting brushes. Here also the bars of the commutator are assembled around a sleeve fixed on the shaft, but are so arranged that their whole length is available for contact with the brushes; being held in position at their ends, with insulation between the V-shaped nicks in the bars and the clamping pieces which enter them.

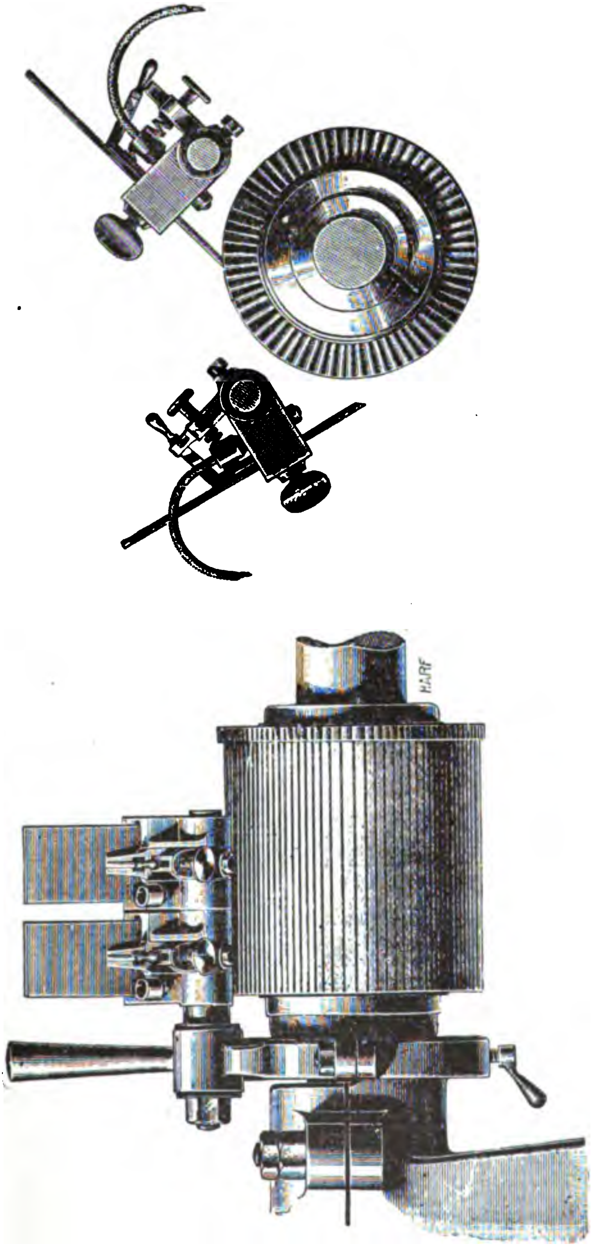
Fig. 271.



Paterson and Cooper's Commutator.

A very similar arrangement obtains in Kapp's dynamo (Fig. 1, Plate II.), in which the clamping nicks in the ends of the bars are made deep; the end insulation being effected by three rings of vulcanized fibre, one flat the other two conical, which fit into the ends of the assembled bars. It is good that a sufficient length of insulating surface should exist between the bars and the metal mountings, for, as in the case of telegraph insulators, there is less likelihood of a fault occurring if the possible leakage-path over a dirty surface is a long path, than if it is short.

In building commutators it is usual to assemble the bars to the proper number, with the interposed pieces of mica,

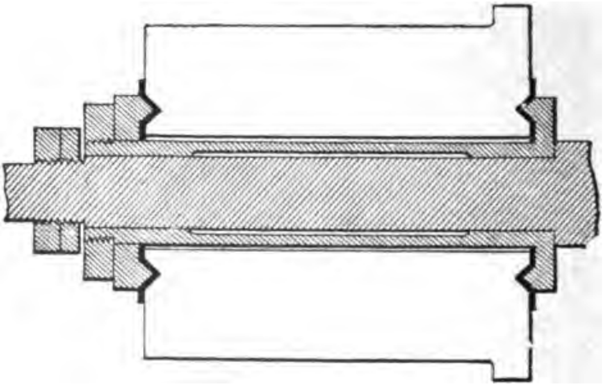


FIGS. 272 and 273.

COMMUTATOR AND BRUSH-HOLDERS OF GULCHER CO.'S 4-POLE MACHINE.

clamping them temporarily around the outside with a strong iron clamp, or forcing them into an external steel ring by hydraulic pressure. They are then put into the lathe and the interior cylindrical surface is bored out. Then the ends are turned up, with the annular hollows to receive the clamping pieces. The whole is then mounted, with proper insulation, upon the sleeve, and the end clamping pieces are screwed up. It is then heated in a stove, and the end clamping pieces are further tightened up. Lastly the temporary external clamps or rings are removed and the external surface is turned up true. The sleeve should be properly keyed or otherwise secured to the shaft, that there may be no slip between it and the armature to which it is afterwards connected. In all the last forms depicted, connexion is made with the armature conductors by means of strips or wires of copper, which are inserted into a cut sawn in the corner of each bar, and firmly held there. A good mode is to rivet the strip connectors into the corners of the bars before they are assembled, each riveted joint being also sweated in with solder.

FIG. 274.



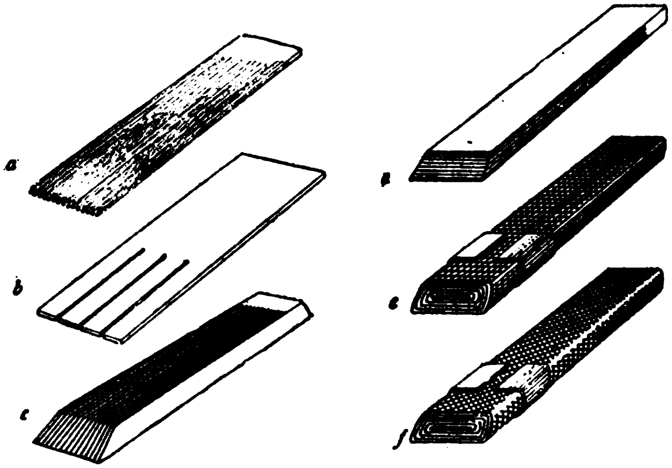
GULCHER CO.'S COMMUTATOR. (Section.)

It is important that these connecting strips should be properly attached, since they are subjected to considerable mechanical forces. Twice in each revolution each such strip carries a strong current; and, owing to the existence of a stray magnetic field, is consequently racked toward one side. Before this was understood it gave rise to frequent accidents.

In some large recent machines there is no separate commutator; the brushes trailing against some part of the copper conductors of the armature winding themselves. This is the case with the great Siemens dynamo at Berlin (Plate XI. and Fig. 256, p. 360); the Edison Company's multipolar dynamo (Plate XIII.); and the Willson dynamo.

Brushes.—The kind of brush most frequently used for receiving the currents from the collector, consists of a quantity of straight copper wires laid side by side, soldered together at one end, and held in a suitable clamp. The number of points of contact secured by this method is advantageous in reducing sparking. Two layers of wires are often thus united in a single brush, as shown in Fig. 275 *a*.

Fig. 275



Different Kinds of Brushes.

Brushes are also made of broad strips of springy copper slit for a short distance so as to touch at several points, Fig. 257 *b*. Such are used in the Brush and Thomson-Houston arc-light dynamos. This kind of brush is usually set tangentially to the surface of the commutator, not sloping to it at an angle as is the case with the thicker kinds of brushes.

Edison has used as brushes a number of copper strips placed edgeways to the collector, and soldered flat against one another at the end furthest from the collector, Fig. 275 *c*. Here also, the object in view was the subdividing of the spark at the contact. In some of the Edison machines, a compound brush made up alternately of layers of wire, like Fig. 275 *a*, and slit strips of copper, like Fig. 275 *c*, has been adopted.

Other makers have used a number of very thin copper strips laid over one another as in Fig. 275 *d*, held together in a suitable clamp.

During the past few years gauze brushes have come into fashion, sheets of copper wire gauze being rolled up and compressed as in Fig. 275 *e*. In order to avoid fraying at the front edge it is usual to fold the gauze obliquely, as in Fig. 275 *f;* the wear is then more uniform. Rotating brushes in the form of metal rollers or disks were first used by Holmes (see p. 11), and have also been tried by Gramme, and others have been suggested by Sir W. Thomson and Mr. C. F. Varley.

It was suggested[1] by Professor G. Forbes to replace the brush by a slab of fine-grained and good conducting carbon. Carbon brushes are indeed used now frequently both for dynamos and for motors.

It is usual, for all but the very smallest machines, to place at least two brushes side by side (as in Fig. 330, p. 488), instead of one broad brush. This allows of either brush being removed for trimming and replaced, while the machine is running. It also tends to equalize the wear of the commutator, each brush being separately pressed against the surface. No rule can be given for the number or breadth of brushes that will apply to all cases. Some makers reckon an additional inch breadth of brush for each hundred amperes of output. Nor is it easy to give a general rule for the thickness of brushes. A thickness that will bridge the film of insulation between bar and bar is not sufficient, for each section of the winding requires to be short-circuited for a certain brief time, in order that the current in it may be reversed. The minimum thickness of brush (or breadth of its oblique end) seems to be about 1½ times the thickness of the commutator bar. There is no objection to a greater thickness in those dynamos that have a large neutral zone about the neutral point, or in which the curve of induction (Fig. 55 p. 70) has a broad flat top. But when a brush of great thickness is used another effect arises, namely, a waste in heating owing to the difference of potential between the parts of the commutator respectively in contact with the advance edge and hinder edge of the brush. To reduce this effect it has been proposed to use two thin brushes, one in front of the other, instead of a single thick one, with a certain amount of resistance between them. Messrs. Goolden & Company have used wire brushes with the separate wires oxidized so as partially to insulate them one from the other, their distant ends only being soldered together.

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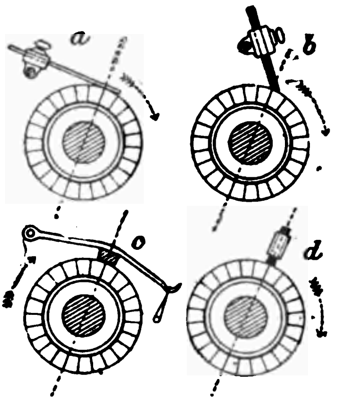
[1] Specification of Patent 1288 of 1885.

FIG. 276.

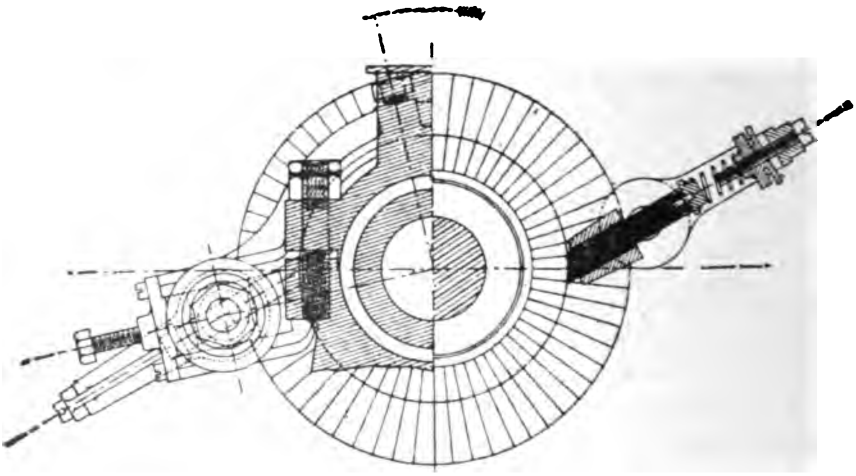


VARIOUS COLLECTING BRUSHES.

The angle at which brushes are set to bear upon the commutator varies with the construction. As a rule the brush is set sloping at an angle, the tip of the brush being raked in the direction of the rotation, so that it may not trip on the edges of the commutator-bars. In Fig. 276 *a*, is shown the case of a brush such as Fig. 275 *b* set tangentially, as in arc-light machines. In Fig. 276 *b* is a thick brush with bevelled end set at about 45°, as in most constant-pressure dynamos. Fig. 276 *c*, shows a form of brush devised by Holroyd Smith for use in motors, permitting of reversal of direction. Blocks of copper or gunmetal are attached to levers furnished with rubber bands to afford contact-pressure. In Fig. 276 *d*, is shown a carbon brush also adapted for use in reversing motors; the brush, a rectangular block of carbon, being pressed radially through a metal slide against the commutator.

In many cases where carbon brushes are used they are set to rake in a direction opposite to the rotation, so that the end-pressure may be greater when running. Fig. 277 illustrates the form of carbon brush-holder designed by Mr. A. T. Snell for use in mining motors.

FIG. 277.



CARBON BRUSH-HOLDER.

Brush-holders and Rockers.—The mechanism for holding the brushes must fulfill certain mechanical and electrical conditions; they are as follows:—

(1.) The brushes must be held firmly, and joined with a good metallic contact to their circuit.

(2.) Brush-holders must permit brushes to be withdrawn or fed forward as required.

(3.) Brushes must be held to make contact at proper angle to the surface of the commutator.

(4.) Brushes must bear with proper pressure upon the commutator; if too light, they will jump and spark; if too heavy they will cut the commutator into ruts.

(5.) Brush-holders must permit brushes to be raised from contact.

(6.) They must also permit, by a proper mechanical catch, of the brushes being held raised out of contact.

(7. Insulated handles should be provided for all dynamos working above 100 volts, so that the brushes may be raised and adjusted without risk of shocks.

(8.) The insulation of the brush, or of brush and brush-holder together, must be very thorough.

A characteristic example of brush-holders is afforded by those of the Gülcher Company's machine, Fig. 273, p. 377. This is a four-pole machine (cross-connected), and therefore, the two brushes must make contact at two points 90° apart. A very similar example, designed by Mr. W. C. Mountain for the "Tyne" dynamo, is given in detail in Plate XV., which also shows the construction of the commutator and the rocker. The rocker R, in Figs. 1 and 2 of this plate, consists of a wrought iron ring in two parts, which is clamped together by bolts upon a raised rim on the bearing. To this rocker are attached a handle H for shifting it so as to bring the brushes to the neutral point, and a couple of projecting lugs L (one only shown) to carry the brush-holder rods, M. The latter are mechanically secured to the rocker lugs by screw nuts which hold them tightly; but they are electrically kept from making contact with the rocker by the interposition of an insulating brush and washers of ebonite. Upon the rods M are placed the brush-holders A, which can turn hinge-wise upon them. Between the hinges of A is fixed, by a screw F, a middle piece D with a projecting tail. The brush B passes through a slot in A, being clamped by a screw C. The current is brought to the brush-holders by flexible conductors, which are soldered into sockets provided for the purpose. The brush is pressed forward by a compressed spiral spring, the force of which can be regulated by a screw through the projecting tail of D; whilst it can be held off by means of the catch K, which can be pulled back and slipped into a cleft on the end of D. In Fig. 273, p. 377, which depicts the similar mechanism of the Gülcher dynamo, one of the hold-off catches is caught in the cleft.

The rocker and brush-holders of the Phœnix dynamo are depicted in Plate XV., Figs. 4 and 5. The method of insulating is here the same, but the requisite pressure is obtained by coiling a spring around the rod; and the holding-off catch is a pin which can engage in a cavity in the rod.

The rocker and brush-holders of the Kapp 2-pole dynamo are shown in detail in Plate III. Here the mode of insulating is the same, but the current is led into a thick washer G; the contact-pressure is produced by an extended spiral spring stretched between a lug on the holder A and the fixed tail D; and the hold-off catch K is constituted by a straight spring which engages in a notch on the corner of A and is released by pressing up the piece Q, which is made of hard fibre. P is a pointer for setting the brushes to the right position in the holder.

A somewhat cruder example is afforded by the brush-holders of the Edison dynamo, Plate XIV., Figs. 1 and 2, in which there is no hold-off catch, but the brushes are raised when required to be held off, by turning the screw that tightens the contact-spring.

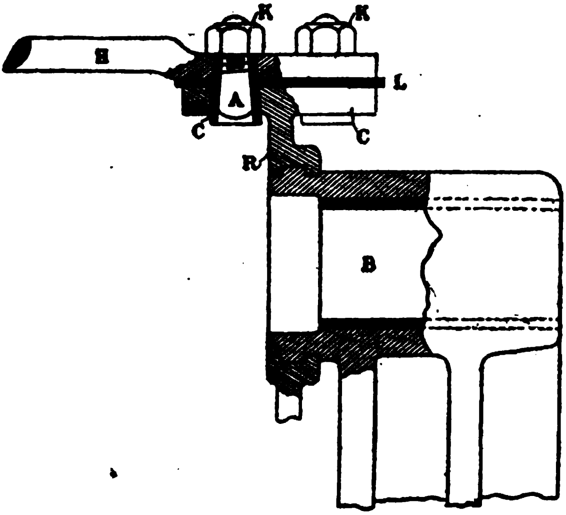
Another set of arrangements of brush-holder, rocker, and catches is depicted in Plate XIX., giving the details of the "Agir" motor.

A defect in the method of insulating by means of a bush upon the brush-holder rod, is its liability to permit the rod to turn. A more solid construction is that of Messrs. Barley and Stevenson, Figs. 278, who flatten out the end of the holder-rod H, and clamp it to an expansion of the rocker R by means of two conical bolts A; insulation being secured by an interposed layer L, and two conical bushes C of ebonite or fibre.

An excellent form of brush-holder, which permits the brushes to be fed forward longitudinally by a screw motion as required, has been devised by Messrs. Goolden & Co., and has a cam-motion for holding-off.

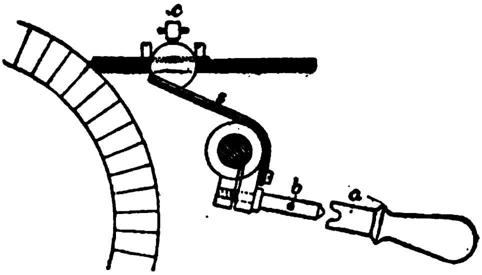
Various inventors have tried to simplify the construction; amongst them, Parsons has proposed to substitute weights for springs to give the requisite pressure.

FIG. 278.



BARLEY AND STEVENSON'S INSULATED BRUSH-HOLDER ROD.

FIG. 279.



SIEMENS AND HALSKE'S BRUSH-HOLDER.

A very simple and effective form of brush-holder, introduced by Siemens and Halske, is used largely in Germany. In this form, Fig. 279, the clamp which holds the brush is set on the end of a curved support *s* made of several thicknesses of springy sheet brass. This is simply clamped to the holder-rod by a clamp screw *b* which admits of the holder being shifted along the rod, or of being turned to give greater or less pressure. The tool *a* is used for any of the required adjustments. These brushes are used with the large multipolar dynamos, such as that figured in Plate XI.

BRUSHES AND COLLECTORS FOR ALTERNATORS.

Alternators have no commutator, but they usually need a pair of sliding contacts to convey the currents to and from the rotating part. The usual device is a pair of contact rings of copper or gun-metal mounted on insulating hubs on the shaft, with one or more brushes to press on each contact-ring. In those alternators in which the revolving part is the armature, great care must be taken to insulate well the two rings from each other, and from the shaft. A deep projecting rim of ebonite should be provided between the two rings if they are situated on the same side of the machine, as in the Blakey-Emmett alternator, Plate IX. Fig. 3 and Plate XXIII. Fig. 1, or as in the Westinghouse alternator, Fig. 423, or the Hopkinson alternator, Fig. 425. In Kapp's alternator, Fig. 421, the contact rings are on opposite sides of the armature, so that not only is high insulation easy, but the risk of accidental shock is lessened. Two brushes are often applied to each ring, so as to admit of replacement while running. In Ferranti's alternators there is a special collecting arrangement, Fig. 435.

In those alternators in which the revolving part is the field-magnet, contact rings and brushes are needed to bring in the exciting current. But, as the current is small and at low voltage, the collecting arrangements are simple and need no special care in insulation. In the slow-speed three-phase alternators constructed by Brown (Plate XXVIII., Fig. 1) the exciting current is conveyed in through two belts of flexible standard wire running over gun-metal pulleys.

CHAPTER XV.

MECHANICAL POINTS IN DESIGN AND CONSTRUCTION.

EVERY dynamo and motor being a piece of running machinery, it is needful to consider the mechanical rules that apply to the design and construction of the various parts.

In Chapter XIII. are considered the mechanical modes of transmitting the power from the shaft to the armature conductors and *vice versâ*. The design of dynamo shafts, journals, bearings, pedestals, and pulleys is a matter equally requiring a knowledge of mechanical principles and practice. Such standard works as Unwin's *Machine Design* should be followed. Nevertheless there are some points in which the ordinary engineering rules cease to be entirely applicable; and it is because of this circumstance that it seems desirable to give the information embodied in the present chapter.

Pressure on Bearings.—In addition to the ordinary pressures on bearings, due to weight of the shaft and its attachments, and to the lateral drag of the driving-belt, there is in dynamo-machines a third cause producing pressure, namely, the actual magnetic pull which the field-magnets exert on the armature core. This is notably great in the case of dynamos having a single magnetic circuit. An example in which the field-magnet tends to lift the armature is afforded by those machines, such as the Edison-Hopkinson, Fig. 352, p. 519, in which the magnet stands over the armature; whilst contrary examples are furnished by machines in which the armature is above the field-magnets, as in the Kapp dynamo, Plate I., and Fig. 330. If the armature is perfectly centred there will always be a tendency to drag it in such a way as to make the entire magnetic circuit more compact. This can be partially obviated by placing it eccentrically, slightly below the centre of the bored polar faces in machines of the under-type, and slightly above the centre in the over-type. In Kapp's machine the downward pull is partly compensated by leaving the pole tips wider apart below the armature than they are above it; or by using cast-iron pole-tips below and wrought-iron pole-tips above. This magnetic pull may amount to as much as four or five times the weight of the armature. For example, in a dynamo built by the Alsacian Company[1] for an output of 60 kilowatts, the magnetic pull on the armature was equal to a weight of no less than 1500 lbs. (See Fig. 284, p. 432).

Gyrostatic Action of Armature.—Another point, which arises only in the case of dynamos used on shipboard and of motors running round a curve on a track, is the gyrostatic action of the revolving armature, which tends always to keep its axis pointing in the same direction. Sir William Thomson, who first directed attention to this matter, has given[2] the following formula for the gyrostatic force on a bearing.

$$F = \frac{W k^2 \Omega \omega}{g l}:$$

where F is the force, in lbs.; W weight of armature, in lbs.; l length between bearings, in feet; g the acceleration of gravity (32 feet per second); ω the angular velocity of the armature, in radians per second; Ω the maximum angular velocity of roll of ship, also in radians per second; k the radius of gyration of the armature in feet.

Example.—In a ship rolling 20°, with a periodic time of 16 seconds, a Siemens alternate-current dynamo (Fig. 426) running at 1300 revolutions per minute; $W = 148$ lbs.; $k = 0{\cdot}7$ foot; $l = 1{\cdot}4$ foot. Here $\Omega = 2\pi \times \frac{20}{360} \times 2\pi \div 16 = 0{\cdot}137$; and $\omega = 2\pi \times 1300 \div 60 = 136$. Then $F = 30{\cdot}6$ lbs. on each bearing, alternately acting up and down at each roll, if the axis of the dynamo lies athwart the ship.

It is evident from these considerations that it would be inexpedient on ship-board to employ dynamos having armatures which resemble fly-wheels in form, if the pressure due to the weight of the armature were not relatively much greater. Drum-armatures of length greater than their diameter are preferable for ship-lighting.

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[1] *Electrical Review*, xxv. 292, 1890.

[2] See Jamieson on Electric Lighting for Steamships, *Proc. Inst. Civil Engineers*, lxxxix. Nov. 11, 1884.

Journals.—From what has been said it will be clear that caution must be used in applying the ordinary rules of machine design. It is usually assumed that journals are made larger for higher speeds, because of the necessity of getting rid, by the greater cooling surface, of the heat generated at the higher speed. But it is known that this assumption leads to the rule

$$l = \frac{F\,n}{\beta};$$

where l is length in inches; F the force (in lbs.) on the bearing; n the number of revolutions per minute; and β a constant which, according to various authorities, may vary between 66,000 and 1,000,000. With such a variation, the rule is almost useless as a guide to design; moreover it takes no account of the diameter of the journal. In all good engineering practice the ratio between the diameter and length of a journal bears a relation to the speed. For slow speeds, such as 100 revolutions per minute, the length need be no greater than one diameter; whereas for speeds of 1000 and upwards the length is five to six diameters, and in high-speed fans sometimes as much as eight diameters.

From this we get the approximate rule:—

$$\frac{l}{d} = 1 + 0{\cdot}004\,n.$$

The rule given above, which is an ordinary one for mill-shafting, is known not to apply to crank-shaft bearings, where centrifugal force is of little importance, but where there come heavy alternately-directed thrusts and wrenches. Still less can it strictly apply to dynamo-machines. In these, for the most part, the power is transmitted through a few inches of shaft from a pulley to the armature. The journal between these two parts, if the pulley is outside, is obviously sustaining a much severer wrench than the journal at the other end; it is in many dynamos made larger and longer than that at the commutator end.

The following data were principally furnished to Professor Perry by students of the Technical College, Finsbury:—

TABLE OF JOURNAL SIZES.

Dynamo and description of Armature.	Revolutions per Minute.	Distance between bearings (inches).	H.P.	Length l (inches.)	Diameter d (inches).	Ratio $l \div d$.
Brush 2-lighter (ring)	1120	17	2	5 5	1·25 1·25	4 4
Edison (1882 type) (drum) 150-light	890	54	15	11 11	2·75 2·75	4 4
"Manchester" (ring)	1600	26	6	3·75 3·75	1·4 1·4	2·68 2·68
Elwell-Parker (drum)	1300	30	10·8	6	1·62	3·7
Elwell-Parker (drum)	630	53	45	9	2·5	3·6
"Victoria" (Mordey) (discoidal ring)	2000	10	2	4 3·25	0·7 0·7	5·71 4·6
Ferranti alternator (star-disk) (1883)	1700	28	10	9 5·25	1·5 1·25	6 4·5
Kapp	780	34	30	10 8·5	2·25 2·25	4·4 3·77
Brown	500	56	35	9·75 9·75	2·0 2·5	4·88 3·9
Ferranti alternator (1889)	120	85	1250	57	14	4
Mordey alternator (Field-magnet revolving)	500	53·75	100	13 13	4·5 4	2·88 3·25

The safe diameter for a journal to give requisite strength depends on the load tending to bend it, as well as on the mere twisting-moment that results from the power transmitted through it. The diameter of a shaft is usually calculated from the formula, applicable when there is no bending:—

$$d \text{ (inches)} = c \sqrt[3]{\text{HP} \div \text{revolutions per minute}};$$

where $c = 2{\cdot}9$ for steel shafts.

The lateral loading of an overhung pulley, due to the belt, produces a considerable amount of bending. Taking the ratios of breadth of pulley to diameter which are usual in dynamo manufacture, it will be found that c ought to be taken as having a value variously estimated from 4·2 to 5·5.

Again, the spindle or shaft of a dynamo is subjected to bending by the weight of the armature, by the magnetic drag on its core, and in belt-driven machines by the lateral drag of the pulley. When running, it is also subjected to bending stresses if the masses it carries are not properly balanced. If the brasses of the bearings keep the journals in line, it is evident that all such actions tend to bend the shaft at definite points. In machines with discoidal armatures a greater length of shaft is free to bend than in those with drum and cylindrical ring armatures, which stiffen the middle portion.

By taking the bending moments due to want of balancing into account, Professor Perry shows that the dependence of length of journal upon speed, hitherto looked upon as good in practice, but having no basis in theory, is really explicable. His result is that for discoidal armatures,

$$\frac{l}{d} = n \sqrt{\mathrm{L}} \div 1000\,;$$

and for drum and elongated ring armatures,

$$\frac{l}{d} = (n \sqrt{\mathrm{L}} \div 3500) + 2,$$

where L is the length of the shaft between the middle parts of its bearings, in inches; and n, l, and d, as before.

Journals, if plain, are usually terminated by collars or raised shoulders, to bear against the brasses and limit end-play. In some forms of machine end-play is specially provided for, so as to cause an even wear at the commutator.

For dynamo spindles the most suitable material is steel, Bessemer steel being usually employed.

In some British machines, chiefly small ones, and others of American make, a shaft of the same diameter throughout is used, with collars shrunk on to prevent end-play. This is not good engineering. A shaft ought to be as thoroughly designed for its work as any other part of the machine. It is well recognized in machine design that where an axle has to bear a transverse load tending to bend it between the points of support, it must be thickest where the bending moment is greatest. One takes as a basis of calculation the diameter appropriate at the journals (found as above) and, assuming that the shaft is of circular section, calculates the diameters at the other parts by the rule that the diameter at each point should be proportional to the cube root of the bending moment at that point.[1] It must not be forgotten that where key-ways are to be subsequently cut for securing the spiders or other attachments, additional diameter must be given to admit of this without reduction of strength. An example of an excellent piece of design is afforded by the shaft of Brown's dynamo, Plate IV.; also by those of Kapp's dynamo, Plate II.; and of Mordey's (Victoria) dynamo, Fig. 336, p. 499.

In the first of these examples it will be observed how the armature spiders fit on over the middle portion of the shaft, and the whole is tightened up by a threaded nut against a collar on the shaft. The commutator is built up around another and shorter sleeve, which slips over a slightly reduced part of the shaft, on the other side of the collar. The pulley is within the bearing, not overhung.

In the second, the armature spider is a long sleeve of cast iron, which stiffens the middle portion of the shaft, and is held up by a threaded nut against a collar.

In the third, the armature spider is held between nuts. The pulley is overhung, with a very thick journal between it and the armature, and a thrust-bearing at the commutator end.

Bearings and Pedestals.—Bearings for dynamos are always made divided, so that the armature can be lifted from its bed, and usually with steps of brass or gun-metal seated in an appropriate pedestal. Those who are not familiar with this elementary part of machine design should examine drawings of the pedestals and bearings of various machines; particularly those of the Kapp dynamo, Plate I.; of the "Agir" motor, Plate XIX.; and those of the Ferranti alternator, Plate XXVI. Where long bearings are used they are occasionally made of cast iron instead of gun-metal or brass. More often a soft-metal bearing is used; or rather a soft metal, such as that known as Babbitt's metal, is used as a lining for a step of gun-metal or cast iron; such anti-friction metal being cast into shallow recesses formed for that purpose in the hollow of the step. An alloy named "Magnolia" metal has lately been largely employed for bearings.

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[1] See Unwin's *Machine Design*, p.147.

Thrust Bearings.—In all dynamos with disk or discoidal ring armatures, end-play is inadmissible; and thrust-bearings must be provided similar to those used on screw-propeller shafts with raised collars on the journals. Or, instead, the shaft may be constructed with shoulders somewhat deeper than usual at the journals, to bear against the brasses. The reader should examine the various thrust-bearings in the drawings of the following dynamos: Brush arc-light machine, Plate XVI.; Mordey "Victoria" dynamo, Fig. 336, p. 499; Mordey alternator, Fig. 437; Ferranti alternator, Plate XXVI., Fig. 2. That of the Kapp alternator, Fig. 421, built by Messrs. Johnson and Phillips, is shown in Fig. 280.

Spherical Bearings.—With all long bearings it is of great importance that they should not only be exactly concentric, but that they should also be accurately in line. To permit the steps to adjust themselves to perfect allignment it is now a frequent practice to provide them with a spherical seat; that is to say a spherical or nearly spherical shape is given to the enlarged central portion of the bearings, and this spherical portion is provided with a soft-metal seat on the pedestal.[1] Fig. 281 gives a design by Mr. Ravenshaw used in Goolden & Co.'s dynamos. Messrs. Siemens employ a less satisfactory form of oval instead of spherical outline. The bearings of the Westinghouse alternator closely resemble Fig. 281, but are adapted to longer journals. The great alternators of Ferranti, Plate XXVI. Fig. 2, have thrust-bearings borne upon spherical seats. Ball bearings, resembling those employed in bicycles, have been suggested by Reignier, and have also been tried in the States.

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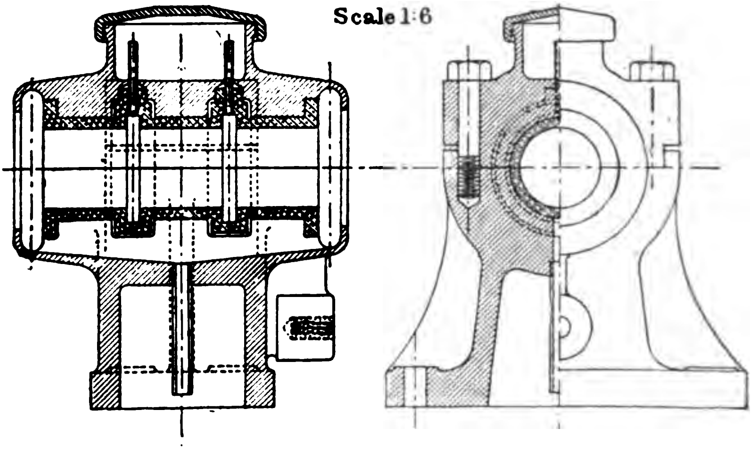
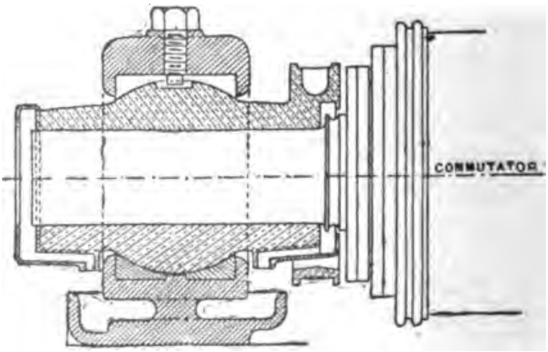
[1] See paper by Mr. Coleman Sellers, in *Journal of Franklin Institute* for 1872, or *Engineering*, xv. 17, or the figure in Unwin's *Machine Design*, p. 170.

FIG. 280.



THRUST-BEARING OF KAPP ALTERNATOR.

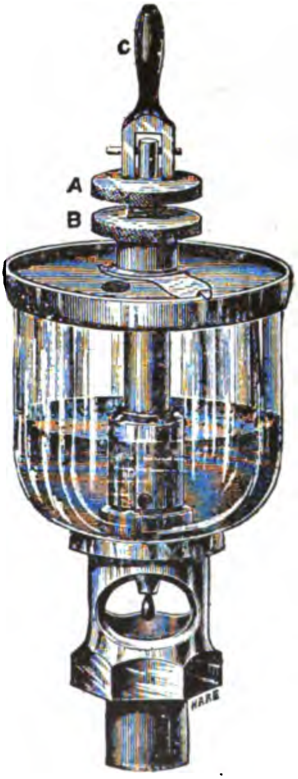
FIG. 281.



SPHERICAL BEARING OF GOOLDEN DYNAMO.

Lubricators.—Provision must be made for lubricating bearings with a due supply of oil or grease, and arrangements to prevent waste and spilling. It is usual to provide an oil-well in the hollow casting of the pedestals, into which the oil drains from the ends of the brasses. Sight-feed lubricators which supply the oil visibly drop by drop are undoubtedly best for ordinary machines. Such a lubricator is illustrated in Fig. 282. The lever C at the top closes the feed of oil when the machine is not wanted to run. The collars A and B regulate the rate at which the oil flows down to drop through the tube-sight below. For ship dynamos special forms that cannot spill oil are preferable. It is usual to provide a collar on the journals to collect and throw off the oil centrifugally, the lips of the bearing being carried (as shown in Fig. 281, above) beyond the brasses, and provided with a re-entrant rim which catches the oil and returns it to the well below. For large dynamos, where there is great weight on the bearings, special precautions have to be taken, as in the lubrication of the bearings of propellor shafts. Oil is supplied under pressure, sometimes from two independent sources, to prevent risk of failure. Such arrangements are the more needful in the case of dynamos, because the motion is one of pure rotation, the shaft not being subjected, like the crank-shaft of a steam-engine, to alternate lateral thrusts, which help to work the oil in under the journals. Sellers has proposed a double lubrication[1] as a safeguard. The ordinary

FIG. 282.



VISIBLE DROP-FEED LUBRICATOR.

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[1] Unwin's *Machine Design*, p. 171.

lubricator supplies oil at the centre of the bearing, and the top brass is provided near each end with a cup containing a stiff mixture of tallow and oil, which only melts in case the bearing heats from failure of the ordinary oil supply. Self-lubricating devices are sometimes used, an oil-well being provided in the lower brass, into which dips a collar on the journal, or a metal ring running loosely over it, or even a mere ring of felt. (See Gramme dynamo, Fig. 325, p. 483.)

Keys and Feathers.—Keys for securing the armature and pulley to the shaft should be of the sunk or flat type, not of the saddle type, which is less reliable. The rules for keys are as follows: b meaning breadth; t thickness; and d diameter of the eye of the hub, all in inches—

$$\begin{aligned} b &= \tfrac{1}{4}\, d + \tfrac{1}{8}''; \\ t\text{, for sunk keys} &= \tfrac{1}{10}\, d + \tfrac{1}{8}''; \\ t\text{, for flat keys} &= \tfrac{1}{11}\, d + \tfrac{1}{16}'': \end{aligned}$$

Where two or more feathers are used on opposite sides of the shaft, the breadth of each may be somewhat less than this. For small machines these numbers are needlessly large; and for less than 5 HP. the formula on p. 390 may be used, with the constant c taken as ·4 or 5.

Pulleys and Belts.—There is no need to give special rules for these, as the ordinary rules for running machinery apply.

Bed-plates.—In designing bed-plates it is usual to save weight of metal by coring out and leaving stiffening ribs and flanges. All this is quite right except in those cases where any part of the bed-plate serves also a magnetic purpose and constitutes a part of the magnetic circuit. For example, in the Paterson & Cooper dynamo, Plate V., the bed-plate serves partially as a yoke for the field-magnet; and in the "Manchester" dynamo of Mather and Platt, Fig. 333, p. 496, as also in Brown's dynamo, Plate IV., the part of the casting which passes under the armature must be left solid. An example of injurious hollowing occurs in Fig. 325, p. 483 (Gramme, 1884). It should also be noted that in the case of machines with drum or cylindrical-ring armatures it is convenient to be able to withdraw the armature longitudinally by removing one pedestal, which should be a separate casting. In that case, for machines of the over-type, it is convenient that the pedestal should be made removable down to the level of the under side of the armature, so that when the upper part is removed the stump may form a convenient resting place for the armature in removal. A case is shown in Fig. 325, p. 484 (Gramme, 1884), and in the Kapp dynamo, Plate I.

Couplings.—When dynamos are driven without belting from a steam-engine on the same bed-plate, it is frequent to connect their respective shafts by a coupling. Of these devices there are several special patterns, such as Brotherhood's, with a connecting part of leather, and Raworth's with flexible steel bands, admitting of a certain amount of play if the two shafts are not in exact alignment. Willans has constructed an ingenious magnetic coupling-clutch.

The questions of the mechanical securing of armatures to shafts, and of the proper strength of binding wires, are discussed in Chapter XIII., on Armature Construction.

CHAPTER XVI.

ELEMENTS OF DYNAMO DESIGN: CALCULATION OF WINDINGS.

THE symbols used in this chapter are explained on p. 209.

As in all designing of machines, so with the designing of dynamos, experience is the ultimate guide. To design a machine which, when driven at a prescribed speed, shall yield any desired number of amperes of current at any given voltage, is a very simple matter to an engineer who has already had experience in designing dynamos of the same general type, but of different output. To a man who has designed two-pole continuous current machines for incandescent lighting it is a simple matter to design another machine of the same sort. But it would be to him by no means so easy from this experience only to pass to designing machines of a multipolar type, or to design alternate-current machines.

It is known, for example, that the number of watts of output of a dynamo of given form, at a given speed, is approximately proportional to its weight. For example: given a dynamo which at 720 revolutions per minute yields (without sparking or overheating) 200 amperes at 105 volts, it is known that using the same iron carcase, and rewinding the machine with new coils equal in weight to those previously used, the machine may be made to give (at same speed as before) 300 amperes at 70 volts, or 250 amperes at 84 volts, or 30 amperes at 700 volts—the product in each of these cases being 21,000 watts. A machine for double the output would have double the weight of iron and double the weight of copper, approximately, if of the same type.

Also, since the voltage is proportional to speed, if a new dynamo had to be designed to give the same output at a speed of 480 instead of 720 revolutions per minute, a carcase about $1\frac{1}{2}$ times as heavy would be required. A manufacturer who had in stock carcases of various sizes would, of course, select the nearest size and wind it with an appropriate winding.

But to begin anew to design a dynamo without this kind of practical basis is a different matter. The first stage in understanding this is to examine carefully the design of some well-established machines, and to see how the dimensions of their several parts are adapted to their functions. It will then be an easier matter to work out any case for a fresh type of machine.

Calculations are needed to ascertain the proper sizes of the parts. Some of these calculations are purely electrical, others magnetic, others mechanical, and some are of a wholly empirical nature founded on experience. If a dynamo is to be constructed to give, say, an output of 200 amperes at 55 volts, the conditions respecting safety from overheating practically determine the size of wire that can be used for the prescribed current: no calculation being needed beyond a reference to such a Table as that in Appendix B, and the knowledge that in armatures of dynamos it is usually quite safe to allow 2000 or more amperes to the square inch. Suppose we settle on a stranded wire of 7 No. 13 S.W.G., which will safely carry 100 amperes (each conductor carries only *half* the armature current). But though this is simple, it is needful to remember that if the field-magnet is shunt-wound, as it must be for ordinary lighting at constant pressure, there will be additional amperes to allow for besides the 200 for the lamps. Let it be taken that 5 amperes, or 2½ per cent. of the current will suffice. Suppose this all settled, then the question arises of the 55 volts. What size of armature, what winding of it, what size of field-magnet will be required; and how must the latter be wound so as to give what is required at the proper speed? Again, it must be remembered that if 55 volts is to be the pressure at the mains, the armature must generate more volts than this —say 57 or 58—to allow a margin for the "lost" volts (p. 252). Suppose this settled, then what is the next step?

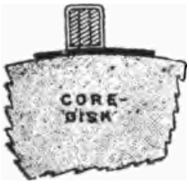
Consider the fundamental equation of the continuous current dynamo (see pp. 47 and 210).

$$E = n \, C \, \mathbf{N} \div 10^8.$$

Now if we assume that the speed n is prescribed beforehand, this formula tells us that the volts of the armature depend on C, the number of armature conductors employed (*i. e.* on the weight of copper), and on **N**, the number of magnetic lines through the armature (*i. e.* on the cross-section of the iron core, and on the degree to which its magnetization is forced up). In the case in question suppose the prescribed speed to be 1140 revolutions per minute, then n (the revolutions per second) = 19. And if E is taken at 57, it follows that C **N** multiplied together must come to exactly 300,000,000. But how much must C and **N** be separately? Well, experience shows that in such machines as this is to be, each armature-section should consist of one, or, at most, two turns, whether wound as ring or as drum. Experience also shows that for 2-pole machines it is convenient if the number of sections (and therefore of bars in the commutator) is a multiple of 6. Also experience shows that if there are fewer sections than 30 there will be fluctuations and possibly spark troubles, and that if there are so many as 150 or upward, there comes in great expense in the construction. We might take 42, or 48, or 54, or 60, or 72, and work out a design on any of these. It is very easy, on completing the calculations, to try another set if the first do not seem quite satisfactory. If there is only one convolution in each section, and the armature is ring-wound, C will be the same as the number of bars of the commutator; but if drum-winding is adopted, then C will be numerically twice as great. Now if C is small, **N** will be large, and *vice versâ;* and we know that to secure sparkless running it is well to keep **N** large and C small (p. 103). Suppose, then, we take C at 72, so that when wound drum-wise there will be 36 sections and a 36-bar commutator. Clearly this will involve that **N** shall equal 300,000,000 ÷ 72 = 4,166,600; in round numbers there must be a flux of 4,170,000 magnetic lines through the core of the armature. Again, experience shows that the proper degree of magnetization to allow in armatures of such machines is (see p. 422) from 12,000 to

17,000 lines to the square centimetre, or say from about 70,000 to 100,000 lines to the square inch. To carry the 4,170,000 lines the armature core ought then to have a nett cross section of about 45 square inches, or, say, 288 square centimetres. But here again comes a choice. How shall we determine this cross-section? What size of core-disk shall we choose, and what total length of core-disks shall we pack together along the shaft? If we take large core-disks of great radial depth we shall only need a comparatively small number of them, and our armature will be short; whereas if we take small core-disks we shall have a long armature. Here two other considerations come in to influence our decision. We have provisionally settled the gauge of copper conductor to carry our current—a stranded wire of 7 No. 13's, of which 3·38 turns will lie side by side in the breadth of an inch. If there are to be 72 such conductors all in one layer, they will occupy about 21 inches side by side. If we allow nothing extra for inserting driving-horns, this will involve core-disks about 7 inches in external diameter. If we say 7½ inches with a 4½-inch hole, the doubled radial depth of iron will be 3 inches; and as there are to be 45 square inches of section of iron that will require a total length of about 15 inches, or, with the insulation between the core-disks, a length of 16 inches, the core of the drum will then be about twice as long as its own diameter. It is usual in drum cores to make the length a little greater than the diameter; but this will do for present purposes. But there is another consideration. If we have got so many complete convolutions of conductor as 36, and each conductor carries 102½ amperes, there will be for total cross-magnetizing effect a product of 3690 ampere-turns. Will this, on the core-disk of 7½ inches diameter be too great—that is to say, so great as to cause sparking? This is purely a question for experience to decide (see p. 436). Now experience shows that in 2-pole drum-wound machines a core-disk 7½ inches in diameter will carry at least 5200 ampere turns without sparking, so that we are well within the limit of sparklessness. We might diminish internal resistances a little by choosing a smaller core-disk, so as to make a longer core that will waste less wire in wrapping across the ends; but in that case we cannot use the stranded wire first selected. If, for example, we chose 6-inch core-disks with 2-inch holes, we should require a nett length of 12 inches, or a gross length of nearly 13 inches. And we could not fit the seventy-two conductors around the periphery unless these were specially made, say of drawn copper strips placed three side by side (as in Fig. 283), each strip being in section 250 mils wide by 60 mils thick. The three overspun together would be about 210 mils thick; and the seventy-two would occupy about 15 inches around the periphery of the 6-inch disk, leaving 3·8 inch for the insertion of driving-horns. Another way of winding would be to use, with 8½-inch core-disks, four wires in parallel, instead of the stranded conductor, each wire being a No. 10 S.W.G., carrying 25 amperes, arranged two deep, there being 144 around the periphery, and occupying about 22 inches side by side. If the manufacturer had in stock no core-disks of these sizes, but had some of 7-inch, he would probably use these, and select a wire to suit. The difference in the final efficiency of the machine would be trifling.

FIG. 283.



Assume then that as the result of all these considerations the 7¼-inch core-disks have been chosen, that the armature core is 15 inches long, and that the insulation and copper windings and binding wires will bring up the external diameter to about 8⅛ inches—it now remains to design the field-magnet.

We will settle upon the form of Fig. 121 as the type, and construct the horizontal limbs of cast iron. We must, provisionally at least, assume a value for the leakage coefficient, which in this type is rather high, say 2·0. Hence we must design the field-magnet to carry 8,340,000 magnetic lines instead of 4,170,000. And, as experience shows that it is not well to force the magnetization beyond about 7000 lines to the square centimetre or 43,000 to the square inch, this implies a cross-section of at least 194 square inches, or about 1191 square centimetres. Again, experience shows that it is well if the armature core extends a trifle beyond the field-magnet on each side. This can be attained by bevelling the edges of the polar parts while keeping the rest broad. Suppose the field-magnet limbs to be made 16½ inches wide from front to back, and 11½ inches in depth; then what length must they be? Obviously a sufficient length to leave room between them for the wrought-iron core and the bobbin large enough to hold the proper amount of winding necessary to excite the magnetization to the prescribed degree. To ascertain the amount of wire that is requisite one has first to calculate the number of ampere-turns by the principle of the magnetic circuit. But how can we apply the principle of the magnetic circuit without knowing the length of iron that is to be used? The method usually adopted here is one of approximation. Make a preliminary calculation in which a rough estimate is inserted for the yet undetermined length of the iron limbs. Having done this, see whether, without mechanical difficulty or risk of overheating, the quantity of wire thus calculated can be wound upon the length of limb so assumed; and having made this comparison, then diminish or increase the length chosen for the limb, and recalculate. But here again comes in a complexity. If we assume that the armature has no demagnetizing reaction, we shall find our calculated quantity of wire much below the quantity actually required. Therefore, calculate approximately by the rule given on p. 285 the number of demagnetizing ampere-turns, and add 2·0 times this to the number previously found; for the field-magnet must be made long enough to carry this additional number of coils. In the case under consideration assume the polar angle to be 145° on each side, it follows that $\frac{145}{180}$ of 72, or about 58 of the conductors of the armature will be in the gap-spaces at any one moment, and that there will be a belt of conductors (see Fig. 71, p. 90), seven broad, exposed between the tips of the poles. This gives us 700 ampere-turns of demagnetizing power if the brushes are assumed to be set near the pole-tips.

Now the external diameter of the armature is 8⅛ inches, and we must allow ⅛ inch clearance all round, making the diameter of the bored polar surface 8¼ inches, and the actual gap-space from iron to iron ½ inch. The gap-spaces themselves may be taken as being 10¾ inches along the curve, and 15 inches from back to front. We are now ready for the rules by which to calculate the field-magnet design. Hence we may pause here in these general considerations, which have been followed far enough to show the need for handy formulæ of sufficient exactness.

ELECTRICAL CALCULATIONS.

§ 1. *To Calculate the Lost Volts in the Armature.*—Measure with an amperemeter the number of amperes i_a flowing through the armature; multiply this by the number of ohms (or fraction of an ohm) that represents the internal resistance of the armature.

$$\text{Lost volts} = r_a \times i_a.$$

A similar mode is to be used for calculating the volts lost by resistance in any coil in series with the armature. If the other internal main-circuit resistances, such as a series coil, are called r_m we must add this to r_a and get

$$\text{Lost volts} = (r_a + r_m) \times i_a.$$

§ 2. *To Calculate the Current going through Shunt.*—Divide volts e at terminals by number of ohms of resistance r_s of shunt coil.

$$i_s = e \div r_s.$$

In a good modern machine i_s may be taken as about 3 per cent. (or less) of i.

§ 3. *To Calculate the Whole Current flowing through Armature.*—Add to the number of amperes i that flow to the lamps, the number of amperes i_s flowing around the shunt coil.

$$i_a = i + i_s.$$

Or about 3 per cent. may be added to the current supplied to the mains.

§ 4. *To find the Gauge of Wire needful for the Armature.*—Remembering that there are two paths through the armature, divide i_a by 2, and then refer to the *Amperage and Wire-Gauge Table*, Appendix B, and select a wire. Remember that in very small machines it is safe to go up to 4000 amperes per square inch, and in large machines to 2000 amperes per square inch.

§ 5. *To find the Whole Electromotive-force Generated in the Armature of a Dynamo.*—Ascertain the number of volts of pressure e, at which the mains are to be supplied from the terminals of the dynamo (depending on the lamps that are to be used): to this add the calculated number of *lost volts.*

$$E = e + r_a \, i_a$$

Then E is the volts which the armature must generate.

§ 6. *To calculate the number of Armature Conductors* C.—This is a matter of experience: see pp. 374 and 400.

§ 7. *To Calculate the Electromotive-force in the Armature. (Continuous Current Machines.)*—Multiply together the revolutions per second n, the number of armature conductors C, and the magnetic flux $\mathbf{N}$, then divide by one hundred million. For:—

1 volt = the cutting of 100,000,000 magnetic lines per second; or

1 volt = 10^8 C.G.S. units of electromotive-force.

$$E \text{ (volts)} = \frac{n \, C \, N}{10^8}$$

[Example: a certain Phœnix dynamo. $n = 23{\cdot}6$; $C = 180$; $\mathbf{N} = 2{,}606{,}000$. Find E.]

EFFICIENCY CALCULATIONS.

§ 8. *To Calculate the Wasted Power in a Dynamo.*—N.B.—To calculate horse-power from the watts divide the number of watts by 746.

(1) Watts wasted in armature coil. Multiply volts lost in armature by amperes in armature: or multiply resistance of armature by square of armature current.

(2) Watts wasted in series coil. Multiply volts lost in series coil by amperes in that coil: or multiply resistance of coil by square of amperes in that coil.

(3) Watts wasted in shunt coil. Multiply amperes in shunt by volts at terminals of shunt: or divide square of volts at terminals by resistance of shunt coil.

(4) Watts wasted by eddy currents not calculable directly.

(5) Watts wasted by magnetic hysteresis. The figures given on p. 163 state the number of watts wasted by hysteresis in well-laminated soft-wrought iron, when subjected to a succession of cycles of magnetization as in the rotating armature core of a dynamo.

§ 9. *To Calculate the Electrical Efficiency.*—Multiply together the useful current i and available volts e, and so obtain the useful watts. Multiply together the total current i_a and total electromotive-force E, and so obtain the total watts of gross output. The electrical efficiency is the ratio of the former to the latter.

$$\eta = e\,i \div \mathrm{E}\,i_a$$

Or it may be calculated by dividing the useful watts by the total watts (useful and wasted added together). The electrical efficiency does not include waste by eddy currents, hysteresis, or friction.

§ 10. *To Ascertain the Commercial Efficiency.*—This is not a branch of designing but belongs to testing. See Chapter XXVIII.

MAGNETIC CALCULATIONS.

§ 11. *To Calculate the Magnetic Flux through the Armature.* —Measure e, add lost volts, and so calculate E, then multiply by 10^8 and divide by n and by C.

$$\mathbf{N} = \frac{\mathrm{E} \times 10^8}{n \times \mathrm{C.}}$$

[Example: An Edison-Hopkinson dynamo. $n = 12{\cdot}5$; $\mathrm{C} = 80$; $e = 105$; $r_a\, i_a = 3{\cdot}26$; find **N**.]

§ 12. *To Calculate the Magnetic Induction* **B** *in an Iron Core.*—Ascertain the magnetic flux **N** through that core; and the nett cross-section A, of iron in that core. Then divide **N** by A.

$$\mathbf{B} = \mathbf{N} \div \mathrm{A};$$

or, if measures are given in squares inches,

$$\mathbf{B}_{\prime\prime} = \mathbf{N} \div \mathrm{A}''.$$

[Example: in an Edison-Hopkinson dynamo $\mathbf{N}$ in armature $= 10{,}826{,}000$; $A'' = 125$ square inch; find $\mathbf{B}_{''}$.]

[Example: in a Kapp dynamo $\mathbf{N}$ in armature $= 6{,}730{,}000$; $A = 403.1$ square centimetres; find $\mathbf{B}$.]

§ 13. *To Calculate the Cross-Section of Iron to carry a given number of Magnetic Lines.*—First determine how many is the total number of magnetic lines that must pass through the armature core when machine is at full work: call this $\mathbf{N}$. Next, settle what is the advisable value to give to the magnetic induction $\mathbf{B}$. In continuous current machines for incandescent lighting it is not usually advisable to push the magnetization further than $\mathbf{B} = 17{,}000$ (to the square centimetre), or $\mathbf{B}_{''} = 110{,}000$ (to the square inch). For arc-lighting machines the magnetization may be pushed further. For alternate-current machines (and also for cores of transformers) a much lower degree of magnetization is desirable: say $\mathbf{B} = 7{,}000$, or $\mathbf{B}_{''} = 45{,}200$. Having settled the value of $\mathbf{B}$ or $\mathbf{B}_{''}$; dividing $\mathbf{N}$ by the value settled will give the required sectional area A or A″.

[Example: in a certain Phœnix dynamo it was decided that $\mathbf{B}_{''}$ should be 115,000 lines per square inch, and $\mathbf{N}$ had to be 2,606,000; find A″.]

[Example: in a Kapp alternator A in the armature core was 103·2 square centimetres; assuming $\mathbf{B} = 6500$; calculate $\mathbf{N}$.]

[Example: in an Edison-Hopkinson dynamo $\mathbf{N}$ in armature $= 10{,}826{,}000$; $A'' = 125$ square inches; find $\mathbf{B}_{''}$.]

For calculating the requisite cross-section of field-magnets a similar process is used, but allowance must be made, as explained later, for carrying a larger number of magnetic lines (because of magnetic leakage); and it is advisable to use, even with wrought-iron cores, a somewhat lower degree of magnetization. If cast-iron cores are used, the section will have to be nearly twice as great, as it is not advisable in that material to force in more than about 8,000 lines to the square centimetre, or than about 50,000 to the square inch.

§ 14. *To allow for Magnetic Leakage.*—In consequence of magnetic leakage the magnetic flux is different at different parts of the magnetic circuit.

[Example: in an Edison-Hopkinson dynamo it was found that to get 10,826,000 lines through the armature, enough magnetizing power had to be put on to make 14,289,000 lines flow through the field-magnet, 3,464,000 of these leaking away and not going through the armature. This is as if out of every 132 lines in field-magnet, 100 only were useful and 32 wasted.]

The symbol for the coefficient of the allowance for leakage is v. Its value varies in different dynamos from 1·2 to 2 or more. In the example above given $v = 1{\cdot}32$. Allowance must be made for v times **N** magnetic lines in the field-magnet in order that there shall be a flux of **N** lines through the armature. (Compare p. 183.)

§ 15. *To find the Permeability of Iron at any stage.*—The ratio between the number of magnetic lines that there are in the iron (or other material) and the number that there would have been (with same magnetizing force) in air, is called the *permeability* of the iron. Symbol μ.

The value of μ is $= 1$ in air, copper, and all non-magnetic materials. In iron it varies with the quality of the metal, and with the degree of saturation to which the magnetization has been pushed, getting smaller as the magnetization is pushed toward saturation. It also differs in different specimens of the same brand of iron from same forge or foundry. Tables I. and II., p. 143, are deduced from data given by Hopkinson in Phil. Trans. of Royal Society, 1885, for two sorts of iron used by Mather and Platt in building Hopkinson's dynamos. The curves, and the values in terms of square centimetres are given on pp. 144 and 145 above.

Suppose **B** has been found from **N** and A as above, and it is desired to know what value μ will be at that stage of magnetization, the designer must refer to the tables or to the curves and see what value of μ corresponds to the value of **B**.

[Example: in armature of Kapp dynamo, when running on open circuit $\mathbf{N} = 6{,}730{,}000$; $A = 403{\cdot}1$ square centimetres; find **B**; and from this, assuming iron is of same quality as in Table I. p. 143, find μ. Also find **B** and μ, when, at full load, **N** is increased up to 7,170,000 by the added magnetizing action of the series coil.]

[Example: in field-magnet (cast iron) of a Phœnix dynamo, $A'' = 62$ square inches; **N** in armature $= 2{,}606{,}000$; v (leakage allowance coefficient) $= 1{\cdot}36$. Calculate v **N**, then $\mathbf{B}_{''}$; then find μ by reference to Table II., p. 146, for cast iron.]

CALCULATIONS RESPECTING MAGNETIC CIRCUIT.

Fundamental Law of Magnetic Circuit.

Magnetomotive-force ÷ magnetic reluctance = the magnetic flux; or, inversely, thus:—

§ 16. *To Calculate the Magnetomotive-force requisite to force a given number of Magnetic Lines through a Definite Magnetic Reluctance.*—Multiply the number which represents the magnetic reluctance by the number of magnetic lines that are to be forced through it. The product will be the amount of the magnetomotive-force.

If the magnetic reluctance has been expressed on the basis of centimetre measurements, the magnetomotive-force, calculated in this way, will require to be divided by 1·257 $\left(i.\ e.\ \text{by}\ \frac{4\pi}{10}\right)$ to give the number of ampere-turns of requisite magnetizing power. If, however, the magnetic reluctance has been expressed in the units explained below, based upon inch measures, the magnetizing power, calculated by the rule given above, will already be expressed directly in ampere-turns.

§ 17. *To Calculate Magnetic Reluctance of an iron core.*

(*a*) *If dimensions are given in centimetres.*—Magnetic reluctance being directly proportional to length, and inversely proportional to sectional area, and to permeability, the following is the formula:

$$\text{Magnetic reluctance} = \frac{l}{A\mu};$$

but the value of μ cannot be inserted until it has been calculated from **B** as above in section 15.

(*b*) *If dimensions are given in inches.*—In this place we apply a numerical coefficient, which takes into account the change of units (2·54 centimetres to the inch), and also, at the same time includes the operation of dividing the magnetomotive-force by $\frac{4}{10}$ of π (= 1·257) to reduce it to ampere-turns. So the rule becomes:—Divide the length (in inches) by the area (in square inches), and by the permeability (formed as above from $\mathbf{B}_{\prime\prime}$), and then multiply by 0·3132. Or in symbols:—

$$\text{Magnetic reluctance} = \frac{l''}{A''\mu} \times 0{\cdot}3132.$$

[Example: find the magnetic reluctance from end to end of a bar of wrought-iron 10 inches long, with a cross-section of 4 square inches, on the supposition that the magnetic flux (**N**) through it will amount to 440,000 lines.]

§ 18. *To Calculate the Total Magnetic Reluctance of the Magnetic Circuit of a Dynamo.*—This is done by calculating the magnetic reluctances of the separate parts and adding them together. Account must, however, be taken of magnetic leakages, by allowing for v**N** lines in the field-magnet cores and yoke.

In the simplest case the magnetic circuit consists of three parts: (1) iron in armature core; (2) air, copper, cotton, &c., in gap-spaces; (3) iron in field-magnet. The permeability of the materials in the gap-spaces may be taken as = 1. Hence the three reluctances in question are respectively written:—

	For centimetre measure.	For inch measure.
1. Armature	$\frac{l_1}{A_1 \mu_1}$	$\frac{l_1}{A''_1 \mu_1} \times 0{\cdot}3132$
2. The Gap-spaces	$\frac{2l_2}{A_2 \mu_2}$	$\frac{2l_2}{A''_2 \mu_2} \times 0{\cdot}3132$
3. Magnet core ..	$\frac{l_3}{A_3 \mu_3}$	$\frac{l''_3}{A''_3 \mu_3} \times 0{\cdot}3132$

If the iron used in armature and field-magnet is of same quality, and if A_3 has been taken equal to v times A_1 so that both are magnetized up to equal degree, μ_3 and μ_1 will be alike. For the gap-spaces $\mu = 1$.

If there were no leakage, the total reluctance would be simply the sum of these three; but leakage reduces the total reluctance, and at the same time obliges us to increase **N** in the magnet, and therefore to increase the ampere-turns.

§ 19. *To Calculate the Ampere-turns of Magnetizing Power Requisite to Force the Desired Magnetic Flux through the Reluctances of the Magnetic Circuit.*

(*a*) *If the dimensions have been given in centimetres*, the rule is:—

Ampere-turns = magnetic flux multiplied by the magnetic reluctance, divided by $\frac{4}{10}$ of π (= 1·257);

or, in detail, the three separate amounts of ampere-turns required for the three principal magnetic reluctances of a dynamo are expressed as follows:—

$$\left.\begin{array}{l}\text{Ampere-turns required to drive}\\ \mathbf{N}\text{ lines through iron of armature}\end{array}\right\} = \mathbf{N} \times \frac{l_1}{A_1 \mu_1} \div \frac{4\pi}{10};$$

$$\left.\begin{array}{l}\text{Ampere-turns required to drive}\\ \mathbf{N}\text{ lines through the two gap spaces}\end{array}\right\} = \mathbf{N} \times \frac{2 l_2}{A_2} \div \frac{4\pi}{10};$$

$$\left.\begin{array}{l}\text{Ampere-turns required to drive}\\ v\mathbf{N}\text{ lines through the iron of}\\ \text{field-magnet}\end{array}\right\} = v\mathbf{N} \times \frac{l_3}{A_3 \mu_3} \div \frac{4\pi}{10};$$

and, adding up:

$$\text{Total ampere-turns required} = \frac{10}{4\pi}\mathbf{N}\left\{\frac{l_1}{A_1 \mu_1} + \frac{2l_2}{A_2} + \frac{vl}{A_3 \mu_3}\right\}$$

(*b*) *If the dimensions are given in inches*, the rule is:—

Ampere-turns = magnetic flux multiplied by magnetic reluctance;

or, in detail:

$$\left.\begin{array}{l}\text{Ampere-turns required to drive}\\ \mathbf{N}\text{ lines through iron of}\\ \text{armature}\end{array}\right\} = \mathbf{N} \times \frac{l''_1}{A''_1 \mu_1} \times 0{\cdot}3132;$$

$$\left.\begin{array}{l}\text{Ampere-turns required to drive}\\ \mathbf{N}\text{ lines through two gap-}\\ \text{spaces}\end{array}\right\} = \mathbf{N} \times \frac{2l''_2}{A''_2} \times 0{\cdot}3132;$$

$$\left.\begin{array}{l}\text{Ampere-turns required to drive}\\ v\mathbf{N}\text{ lines through iron of}\\ \text{field-magnets}\end{array}\right\} = v\mathbf{N} \times \frac{l''_3}{A''_3 \mu_3} \times 0{\cdot}3132.$$

and, adding up:

$$\left.\begin{array}{l}\text{Total ampere-turns}\\ \text{required}\end{array}\right\} = 0{\cdot}3132\,\mathbf{N}\left\{\frac{l''_1}{A''_1 \mu_1} + \frac{2l''_2}{A''_2} + \frac{vl}{A''_3 \mu_3}\right\}$$

[Example: in a certain Lahmeyer dynamo, with cast-iron magnets, the following were the data: $\mathbf{N} = 2{,}328{,}000$; $v = 1{\cdot}11$; $l''_1 = 6\frac{9}{32}$; $l''_2 = \frac{13}{64}$; $l''_3 = 40$; $A''_1 = 34{\cdot}8$ sq. in.; $A''_2 = 69{\cdot}5$; $A''_3 = 86{\cdot}5$; calculate the required ampere-turns.]

In some forms of dynamo the magnetic reluctances of pole-pieces and yokes must be separately calculated; and allowance must in some cases be made for leakages at different parts of the circuit. Hence a more careful formula would be:—

$$\mathrm{S}i = 0{\cdot}3132\,\mathbf{N}\left\{\frac{l''_1}{\mathrm{A}_1\,\mu_1} + \frac{2l''_2}{\mathrm{A}_2} + \frac{v_3\,l'_3}{\mathrm{A}_3\,\mu_3} + \frac{v_4\,l'_4}{\mathrm{A}_4\,\mu_4} + \frac{v_5\,l'_5}{\mathrm{A}_5\,\mu_5}\right\}$$

It is expedient that the calculation of the ampere-turns should be made *twice;* that is once (using the value of **N** that corresponds to the case of no lost volts) to find the value of the ampere-turns of winding to be put on the shunt, when there is no current through the lamps; and once (using the higher value of **N** that corresponds to the maximum E) to find the increased ampere-turns that are required when the full current is being taken from the armature. These will have to be provided for (in compound-wound machines) by a series coil, which also will need to have additional windings to compensate for demagnetizing effect of armature.

§ 20. *To Estimate the Additional Ampere-turns Required to Compensate for the Demagnetizing Action of the Armature Current when the Brushes have a Forward Lead.*

Count the number of conductors on periphery, between the diameter of symmetry and the actual diameter of commutation, and multiply by i_a the amperes flowing through armature. (Approximately half the number of conductors exposed in one of the spaces between the corners of the two pole-pieces may be taken for multiplying.) The product so found should be multiplied by v, and then added to the number of ampere-turns found as in the last paragraph. For ring machines the product must be doubled. Arnoux states that the number is in ring machines about 15 per cent. of the shunt ampere-turns; whilst in drum machines it varies from 5 to 7 per cent.

EXAMPLES OF CALCULATIONS APPLIED TO CONTINUOUS CURRENT DYNAMOS.

As remarked at the opening of the present chapter, it is advantageous to go over the calculation of some existing machines. Two complete examples are given here, one relating to an Edison-Hopkinson dynamo (see pp. 182, 184, and 520); the second to a Phœnix dynamo, Plate V. The magnetic-circuit calculations for the first have been calculated out in C.G.S. units; those in the second and third in inch units, so as to show both modes of calculation. As a third example, an exercise for calculation is given.

EXAMPLE I.—AN EDISON-HOPKINSON DYNAMO.

Description adapted from paper by J. and E. Hopkinson, in *Phil. Trans.*, 1886.

Shunt-Wound Dynamo, with Drum Armature: 33 kilowatts Output: 320 Amperes, at 105 volts, at 750 revolutions per minute.

Armature: Built up of about 1,000 iron core-plates stamped out of soft sheet iron separated by sheets of paper, and held between two end-plates, one of which is secured by a washer shrunk on to the shaft, and the other by a nut and a lock-nut screwed on shaft itself. Shaft of Bessemer steel, insulated before core-plates are threaded on.

Core-disks external diam.	$9\frac{5}{8}$	inch.	24·5	centim.
" internal diam.	3	"	7·62	"
Shaft diam.	$2\frac{3}{4}$	"	6·985	"
Radial depth of iron	$3\frac{5}{16}$	"	8·45	"
Gross length of core	20	"	50·8	"
Total thickness paper insulation ..	$1\frac{3}{8}$	"	3·4	"
Nett length of iron in core	$18\frac{5}{8}$	"	47·4	"
Nett cross section of iron	$123\frac{5}{16}$	sq. in.	801	sq. cm.
Ditto allowing for shaft	125	"	810	"

Core is wound with 40 convolutions (*i.e.* there are 80 external conductors at periphery) each consisting of 16 strands of copper wire 69 mils or 1·753 millimetres in diameter (*i.e.* 15½ B. W. G.) the convolutions being placed in two layers of 20 each. Commutator 40 bars of copper insulated with mica; connections to armature so made that plane of commutation is horizontal when circuit is open. Cross section of the above wire, 0·0037 sq. in. or 2·3 sq. mm.; total ditto of each set of 16 wires 0·0592 sq. in., or 38 sq. mm. Resistance of armature from brush to brush 0·009947 ohm, at 13·5° Centigrade.

Field Magnet: Three forgings of hammered scrap iron, truly faced, and bolted together; section of limbs rectangular with corners slightly rounded. Stands on a zinc footstep, over a cast-iron bed-plate.

	Inch.	Centim.
Length of magnet limb	18	45·7
Breadth of limb (parallel to shaft)	$17\frac{1}{2}$	44·45
Thickness of limb	$8\frac{11}{16}$	22·1
Length of yoke	$24\frac{1}{4}$	61·6
Breadth of yoke	19	48·3
Depth of yoke	$9\frac{1}{4}$	23·2
Distance between centres of limbs	15	38·1
Diam. of bore of polar faces	$10\frac{13}{16}$	27·5
Depth of pole-pieces	9	25·4
Width of pole-piece at narrowest part	$8\frac{3}{8}$	21·3
Breadth of pole-pieces (parallel to shaft)	19	48·3
Width of gap between pole-pieces	5	12·7
Depth of edges of protruding horns	$\frac{5}{16}$	0·8
Thickness of gap-space (from iron to iron)	$\frac{19}{32}$	1·5
Thickness of zinc footstep	5	12·7
Angular breadth of polar face	129°	
Angular breadth of gap	51°	

The magnetizing coils are wound directly on the limbs, and consist of 11 layers on each limb of copper wire 0·100 inch, or 2·413 mm. diameter (No. 13 B. W. G.), having, therefore, cross section of 0·0071 sq. in. or 4·573 sq. mm., making 3,260 convolutions in all; total length being approximately 15,000 feet, or 4,570 metres. Resistance at 13·5° C. is 16·93 ohms.

Data for Calculating Reluctances in Magnetic Circuit.

1.—*Armature Core.*

l_1 taken as $5\frac{1}{8}$ inch or 13 cm.

A_1 taken as 125 sq. in. or 810 sq. cm.

2.—*Gap Space.*

l_2 is $\frac{19}{32}$ inch (= 0·59 inch), or 1·5 cm.

A_2 taken as 248 sq. in. or 1,600 sq. cm. This allows $29\frac{1}{2}$ sq. inch, or 190 sq. cm. for fringing. The actual area of the polar face is $234\frac{1}{2}$ sq. inch. or 1,513 sq. cm.; and the corresponding area of 129° of surface of armature core is $218\frac{1}{2}$ sq. inch, or 1,410 sq. cm. Allow, for fringing, a margin all round equal to four-fifths of gap space.

3.—*Magnet Limbs.*

l_3 is in total 36 inch, or 91·4 cm.

A_3 is taken at 152 sq. inch, or 980 sq. cm.

4.—*Yoke.*

l_4 is taken at 19¼ inch, 49 cm., estimated along quadrants.

A_4 is 173½ sq. inch, or 1,120 sq. cm.

5.—*Pole Pieces.*

l_5 is $4\frac{5}{16}$ inch, or 11 cm., estimated along curve.

A_5 is taken as 190½ sq. inch, or 1,230 sq. cm.; being mean area between section of limb and area of polar face.

Coefficient of leakage v was taken by Hopkinson as 1·32, but was probably nearer 1·4.

CALCULATIONS ABOUT THIS DYNAMO.

$i = 320$; $e = 105$; $n = \frac{750}{60} = 12{\cdot}5$; $r_a = 0{\cdot}01$; $r_s = 16{\cdot}93$, whence $i_s = e \div r_s = 6{\cdot}21$; $i_a = i + i_s = 326$; lost volts $= r_a \times i_a = 0{\cdot}01 \times 326 = 3{\cdot}26$; hence $E = e + r_a\ i_a = 108{\cdot}26$ at full load. $C = 80$.

$$\mathbf{N} = \frac{E \times 100{,}000{,}000}{n\ C} = \frac{108{\cdot}26 \times 10}{12{\cdot}5 \times 80} = 10{,}826{,}000.$$

Useful watts $= e \times i$ $= 105 \times 320 = 33{,}600$.
Total watts $= E \times i_a$ $= 108{\cdot}26 \times 326 = 35{,}293$.
Electrical efficiency η = useful watts ÷ total watts.
" " = 0·952, or 95·2 per cent.
Watts lost in armature = lost volts × amperes;
" " " $= 3{\cdot}26 \times 326 = 1{,}062{\cdot}76$.
Watts lost in magnets = lost amperes × volts.
" " " $= 6 \times 105 = 630$.
Watts lost by hysteresis = 12·5 reversals per sec. in 2·83 cubic feet at 13,360 for **B**, see p. 163.
" " " = 863.

To find ampere-turns requisite to magnetize. By § 19 above;

$$Si = \frac{10}{4\pi} \times 10{,}826{,}000 \times \text{the total magnetic reluctance.}$$

This must be calculated from the 5 data of the magnetic circuit in separate parts, as on p. 410. First find values of **B** in separate parts according to leakage and cross-section, and from these values find corresponding values of μ by Table I., p. 143.

1. Armature ... ... $\mathbf{B}_1 = 13\,360$; $\mu_1 = 1{,}000$
3. Magnet limbs ... $\mathbf{B}_3 = 14\,250$; $\mu_3 = 796$
4. Yoke ... ... $\mathbf{B}_4 = 13{,}530$; $\mu_4 = 895$
5. Pole-pieces ... $\mathbf{B}_5 = 11{,}450$; $\mu_5 = 1{,}566$

Inserting these values and those of the leakage coefficients, the magnetic reluctances come out:—

1. Armature	0·00001605
2. Gap-spaces	0·00187500
3. Magnet limbs	0·00015467
4. Yoke	0·00006845
5. Pole-pieces	0·00000151
Total Magnetic reluctance	0·00211568

Whence

$$Si = \frac{10}{4\pi} \times 10{,}826{,}000 \times 0{\cdot}00211568$$
$$= 18226.$$

To this must be added the ampere-turns needed to compensate for demagnetizing action of armature. The number of armature conductors between pole-tips is 11; but as the diameter of commutation is not quite at the pole-tips we take 9 as the demagnetizing belt. Multiplying this by half the armature current (163 amperes), and by the leakage-coefficient (1·32), we get 1936 as the compensating number, making total requisite ampere-turns 20,162. Dividing this by the number of amperes of current allowed in the shunt coil (6·21) gives 3214 as the requisite number of coils on the field-magnet. The actual number wound on was 3260, which allows a margin for regulating.

Example II; a Phœnix Dynamo (over-type).

Description: Compound-wound Dynamo with Ring Armature 9 to 10 kilowatts, see Plate V., Figs. 1 and 2.

Output: 90 amperes at 105 volts, at 1,420 revolutions per minute.

Armature: built up of about 225 iron core-plates (stamped out of soft sheet iron) separated by sheets of paper and held by four bolts fixed firmly, but with due regard to insulation, through a couple of four-armed spiders keyed to shaft.

Shaft of Bessemer steel.

Core-disks external diameter ...	10⅝ inch	26·99 cm.
” ” internal ”	8 ”	20·32 ”
Shaft diameter	1¾ ”	4·45 ”
Radial depth of iron	1$\frac{5}{16}$ ”	3·33 ”
Gross length of core	9 ”	22·86 ”
Total thickness paper insulation	$\frac{7}{16}$ ”	1·12 ”

Nett length of iron in core .... $8\frac{5}{16}$ inch or 20·11 cm.
Nett section of iron .... 22 sq. inch 141·9 sq. cms.
Thickness of core-disks No. 20, B.W.G. = 0·035 inch.

Core is wound with 36 windings each consisting of 5 convolutions of square copper wire 0·150 in. sq. or 3·81 mm. sq.; the convolutions being placed in one layer. No. of conductors on periphery is 180; commutator 36 bars of cast copper, insulated with mica. Cross section of above wire is 0·0225 sq. in. or about 14·5 sq. mms.

Resistance of armature from brush to brush 0·04 ohms.

Field-magnets: 2 castings, truly faced and bolted together: section of limbs rectangular with corners slightly rounded. The two limbs and a thin connecting-piece are cast in one; the bed-plate which also serves as yoke being a separate piece.

Length of magnet limb	$8\frac{3}{4}$	in. or	22·22	cm.
Breadth of limb (parallel to shaft)	9	„	22·86	„
Thickness of limb	7	„	17·78	„
Length of yoke	$21\frac{1}{2}$	„	54·61	„
Breadth of yoke	9	„	22·86	„
Depth of yoke	6	„	15·24	„
Distance between centres of limbs	$13\frac{1}{2}$	„	34·29	„
Diam. of bore of polar faces	$11\frac{3}{8}$	„	28·89	„
Depth of pole pieces	$9\frac{1}{2}$	„	24·13	„
Breadth of pole pieces (parallel to shaft)	9	„	22·86	„
Width of gap between pole pieces	$6\frac{1}{2}$	„	16·51	„
Thickness of gap-space (iron to iron)	$\frac{3}{8}$	„	0·95	„
Angular breadth of polar face	112°			
Angular breadth of gap	68°			

The magnetizing coils consist of a shunt as well as a series winding on each coil, and are wound on rectangular bobbins which are afterwards slid on to the limbs.

The series winding consists of 54 turns of copper wire (0·203 inch or 5·156 mm. diam.) No. 6 B.W.G. on each coil, having a cross section of ·032 sq. inch, or 10·645 sq. mm. Resistance of the series winding is ·021 ohms. Approximate length of series coils is 51 yards, or 46 metres. The shunt winding consists of 1727 turns on each coil (in all 3,454 turns) of copper wire 0·057 inch or 1·445 mm. diam., having a cross section of ·00255 sq. inch or 1·645 sq. mm. Resistance of shunt winding is 39·76 ohms. Length of shunt winding is approximately 1900 yards, or 1730 metres.

Ratio of inner to outer diameter of core is 7·53 to 10.
" radial depth of iron to extl. diam. of
core is .... 2·47 „ 10.

Ratio of length of iron in core to diam. of core is .... 8·88 to 10.
" of depth of copper to depth of iron in core .... 1 " 8·5
" of depth of copper to external diam. of core .... 1 " 71

Data for calculating Reluctances of Magnetic Circuit.

1. *Armature core:—*
   l_1 taken as $6\frac{1}{2}$ inch, or 16·51 cms.
   A_1 taken as $21\frac{13}{16}$ sq. inch, or 140·8 sq. cms.
   μ_1 taken at 195.
2. *Gap-space:—*
   l_2 is $\frac{3}{8}$ inch, or ·95 cms.
   A_2 taken as 127 sq. inch, or 820 sq. cms.
3. *Magnet-limbs:—*
   l_3 is in total $17\frac{1}{2}$ inch, or 44·4 cms.
   A_3 is in total 62 sq. inch, or 340 sq. cms.
4. *Yoke:—*
   l_4 taken as 12 inch, or 30·48 cms.
   A_4 taken as 90 sq. in., or 580·5 sq. cms.
5. *Pole-pieces:—*
   l_5 taken as $8\frac{13}{16}$ inch, or 22·38 cms.
   A_5 taken as 81 sq. inch, or 490 sq. cms., the mean between section of limb and polar surface.
   Coefficient of leakage taken as 1·4.

Calculations about this dynamo:—

$i = 90$ amperes. $e = 105$ volts. $n = \frac{1420}{60} = 23{\cdot}6$.

$r_s = 39{\cdot}76$ ohms. $i_s = \dfrac{e}{r_s} = 2{\cdot}548$ amperes.

$i_a = i + i_s = 92{\cdot}548$ amperes.
$E = e + (r_a + r_m)\, i_a = 110{\cdot}7$.
$N = 2{,}606{,}000$, at full load; or $2{,}472{,}000$ on open circuit.
Useful watts $= e \times i$ $= 105 \times 90 = 9450$.
Total watts $= E \times i_a$ $= 110{\cdot}7 \times 92{\cdot}5 = 10{,}240$.
Electrical efficiency η = useful watts ÷ total watts.
" " $= 92{\cdot}3$ per cent.
Watts lost in armature $= r_a\, i_a^2$.
" " $= 342$.
Watts lost in series coil $= r_m\, i_a^2$.
" " $= 180$.
Watts lost in shunt coil $= e\, i_s$.
" " $= 265$.

It will be noticed that in enumerating the dimensions selected for calculation, the nett length for the induction path through the armature has been taken at $6\frac{1}{2}$ inches, or only equal to the width between the polar horns. The ring in this machine being very thin, the distribution of the magnetic flux through it is somewhat like that shown in Fig. 48, p. 63; the actual length of path along which the whole of the flux is confined to the mere radial depth of the core is actually less than the distance between the polar horns.

To find ampere-turns requisite to magnetize; apply rule of § 16, p. 409.

$$S\,i = \mathbf{N} \times \text{total effective magnetic reluctance.}$$

The total effective reluctance (allowing for leakage) for the five separate terms is:—

$$\Big\} \frac{6\frac{1}{2}}{21\frac{13}{16} \times \mu_1} + 2\,\frac{\frac{3}{8}}{127} + \frac{17\frac{1}{2} \times 1{\cdot}4}{62 \times \mu_3} + \frac{12 \times 1{\cdot}4}{90 \times \mu_4} + \frac{8\frac{13}{16}}{81 \times \mu_5} \Big\{ \times 0{\cdot}3132.$$

The values of μ in the separate parts have to be found from tables as those on p. 146, from the corresponding values of $\mathbf{B}_{\prime\prime}$.

		$\mathbf{B}_{\prime\prime}$	μ	Reluctance.	Ampere-turns needed.
Open Circuit.	1. Armature ..	113,200	195	0·000484	1106
	2. Gap-spaces ..	24,720	1	0·001885	4660
	3. Magnet Limbs	49,360	140	0·000901	2227
	4. Yoke	32,000	425	0·000141	349
	5. Pole-pieces ..	37,700	291	0·000121	299
			Total	0·003532	8731
Full Load.	1. Armature ..	119,300	75	0·001260	3115
	2. Gap-spaces ..	26,060	1	0·001885	4630
	3. Magnet Limbs	58,500	80	0·001576	3896
	4. Yoke	40,530	240	0·000248	615
	5. Pole-pieces ..	45,040	190	0·000185	457
			Total	0·005154	12741

As the shunt winding alone acts when the machine is on open circuit, it must provide 8731 ampere-turns; and the series winding at full load must not only provide the additional

4010 to make up to 12,741 as shown above, to compensate for lost volts and the increasing saturation, but must also provide additional windings to compensate for demagnetizing effects.

Actual excitation of this dynamo was:—

Ampere-turns.	
8800	on open circuit.
2250	added by series winding to compensate for lost volts due to resistance assuming diminished permeability.
2550	added by series winding to compensate demagnetizing effect of armature and loss of volts due to lead of brushes.
13,600	= total actual excitation at full load.

At 1,420 revolutions per minute machine gives out:—

Amp.	0	32	42	67·5	79·5	91
Volts.	103	104	105	105·2	105·2	104

Example III. (already partly considered on pp. 399 to 404).

Design of a single-field compound-wound dynamo, with drum armature. Output 200 amperes at 55 volts at 1140 revolutions per minute. It is required to find the appropriate field-magnet.

Armature.—Built up of core-disks, separated by varnished manilla paper fixed by end-clamping upon a three-webbed sleeve of gun-metal. Shaft of Siemens steel. Commutator 36 parts. Conductors 72 all round periphery, in one layer. Hence at full load **N** must be about 4,170,000 lines; and at 90,000 lines to square inch this needs a net cross-section of 45 square inches in core. Core disks, 7¼ inches exterior diameter, 4¼ inches interior diameter, in sufficient numbers to make up total net length of 15 inches. Core-disks are 28 mils (*i. e.* No. 22 S.W.G.) thick, so that about 536 of them are needed. Conductor, a stranded wire of 7 No. 13, overspun together with double cotton covering, and already lightly varnished with Scott's rubber varnish. Resistance of armature from brush to brush 0·007 ohms ; length of armature winding, approximately 52 yards.

Field-magnets.—Horizontal limbs of best cast iron carefully annealed, lower one forming part of bed-plate casting. Section widening from lips so as to have section 194 square inches, and at parts furthest from armature 16½ inches wide by 11 inches deep, being bored out to receive the ends of the wrought-iron magnet core, which is a round forging, 10½ inches diameter, turned down at its ends to 10 inches diameter, where it is inserted into the horizontal pole-pieces. The finished machine generally resembles Fig. 359, page 531, but is more massive in the field-magnets.

To find the proper length for this core make first an approximate estimate of the needed number of ampere-turns, and thence calculate the quantity of windings and the proper length of core to receive the wire. Then design the magnetic circuit to be as compact as possible; and having so settled the sizes of the parts, calculate more exactly, as in the preceding example, the requisite number of ampere-turns to be provided on open circuit and at full load.

USEFUL POINTS IN DESIGNING.

Peripheral Speeds.—The usual peripheral speeds appear to be from 2700 to 3000 feet per minute (*i.e.* 12 to 15 meters per second) for drums and cylindrical rings. Esson maintains that 6000 feet per second can be safely attained in large machines. For discoidal rings and disk armatures, 3000 to 5000 feet per minute is usual. Ferranti's 15 foot armatures (Plate XXVI., Fig. 2) have peripheral speed of 5400 ft. per sec. Those alternators in which the field-magnet revolves may have higher peripheral speeds without risk of flying to pieces, some going over 7000 feet per minute.

Core-disks.—These are usually from 25 to 50 mils in thickness, whether for ring or drum cores.

For rings, the ratio used in practice between the external and internal diameters is from 10 to 8 in small rings to 10 to 7 in large rings. In Brown's four-pole rings (Plate VIII.), the ratio is 10 to 7; in his eight-pole rings (Plate X.) about 10 to 8. In Siemens' machines with internal magnets (Plate XI.), the ratio is about 10 to 9. In machines with cast-iron magnets, the rings are usually made with a less radial depth of iron than in machines of wrought iron.

For drums, the usual ratio of external and internal diameters is 10 to 3. In Kapp's two-pole machine (Plate I.), the ratio is 7 to 4.

Limit of Magnetization.—The limiting values to which it is found expedient in practice to push the magnetization have been several times alluded to. The values of **B** are here tabulated for convenience.

B = Lines per sq. cm.

Species of Dynamo.	In Armature.	In Gap Space.	In Field-Magnet.	
			Wrought Iron.	Cast Iron.
Constant Potential Machines.				
2-Pole Drum.	10,000 to 15,000	4,000 to 7,500	12,000 to 17,000	6,000 to 8,000
2-Pole Ring (long).	12,000 to 16,000	2,500 to 5,000	12,000 to 17,000	6,000 to 8,000
Multipolar Rings.	10,000 to 15,000	3,000 to 5,000	12,000 to 17,000	6,000 to 8,000
Arc-Light Machines.	17,000 to 20,000	3,000 to 7,000	17,000 to 20,000	6,000 to 10,000
Alternators.				
Multipolar Ring.	6,000 to 6,500	2,500 to 4,000	12,000 to 17,000	6,000 to 8,000
" Drum.	6,000 to 7,000	2,500 to 5,000	12,000 to 17,000	6,000 to 8,000
Coreless Disk.	5,000	5,000	12,000	6,000

Size of Wire for Winding Armatures.—This will be further discussed under heading of permissible heating. It may be here remarked that modern practice allows from 2000 to 3000 amperes per square inch, in conductors of ring armatures, and even up to 4000 amperes per square inch in those of drum armatures. But in the magnet coils, only about 2000 amperes per square inch. Esson[1] has given the following table of usual sizes of wire (double cotton-covered and varnished) used in winding armatures to run at usual speeds, together with the number of layers of each that may be used for these currents without overheating.

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[1] *Electrical Review*, xxvii. 546, 1891.

Amperes to be carried.	Diameter of bare wire, in mils.	Number of layers.
5	48	4
7·5	62	3
10	75	3
20	90	2
22·5	2 × 75	2
25	3 × 65	3
32·5	2 × 80	2
37·5	126	1
40	2 × 90	2
50	2 × 109	2
50	148	1
60	180	1
75	203	1
90	238	1

The length of wire to produce a given voltage at a given speed is a measure (inversely) of the density of the magnetic field. The following are examples of 2-pole drum-wound dynamos. Edison-Hopkinson, at 750 revs. per min., takes 19 inches per volt. Kapp, at 780 revs. per min., takes 35 inches per volt. Thomson-Houston arc lighter, at 900 revs. per min. takes 148 inches per volt.

Heating of Magnet Coils.—All field-magnet coils are liable to heat, because even the purest copper offers resistance. If it be assumed that the thickness of the insulation is proportional to the thickness of the wire on which it is wound, it follows that the weight of copper in a coil filling a bobbin of given dimensions will be the same, whether a thick wire or a thin one be employed. Further, for a given volume to be filled with coils, the number of *ohms* of resistance of the coil will vary *directly as the square of the number of turns* in the coil. For if a coil wound with 100 turns of a given gauge be rewound with 200 turns of a wire having half the sectional area, the resistance of this new winding will obviously be four times as great as that of the original winding. Also, by a similar argument, it follows that the resistance of a coil of given volume will vary *inversely as the square of the sectional area* of the wire used. And as this area is proportional to the square of the diameter of the wire, it follows that the resistance is *inversely proportional to the fourth power of the diameter* of the wire used. (See also p. 430.)

The amount of heat developed per second in a coil is the product of the resistance into the square of the strength of the current. To avoid waste, therefore, no unnecessary resistance should be introduced into any main-circuit coil. It is easy to show that with a coil of *given volume*, the heat-waste is the same for the same magnetizing power, no matter whether the coil consists of few windings of thick wire or many windings of thin wire. The heat per second is $i^2 r$, and the magnetizing power is $S i$; i being the current, r the resistance, and S the number of turns. But r varies as the square of S, if the volume occupied by the coils is constant. For suppose we double the number of coils, and halve the cross-sectional area of the wire, each foot of the thinner wire will offer twice as much resistance as before; and there are twice as many feet of wire. The resistance is quadrupled therefore. The heat is then proportional to $i^2 S^2$: and therefore the heat is proportional to the square of the magnetizing power. If, therefore, we apply the same magnetizing power by means of the coil, the heat waste is the same, however the coil is wound. To magnetize the field-magnets of a dynamo to the same degree of intensity requires the same expenditure of electric energy, whether they are series wound or shunt wound, provided the volume is the same. But if the *volume* of the coil (and the weight of copper in it) may be increased, then the heat-waste may be proportionally lessened. For example, suppose a shunt coil of resistance r has Z turns, if we wind on another Z turns in addition, the magnetizing power will remain nearly the same, though the current will be cut down to one-half owing to the doubling of the resistance; and the heat loss will be halved, for $2r \times (\frac{1}{2} i)^2$ will be $\frac{1}{2} i^2 r$.

In fact one ought to wind on so much copper wire that the annual interest on the prime cost is approximately equal to the annual cost of the electric energy spent in the inevitable heating.

It is assumed in the foregoing argument that we get double the number of turns on if we halve the sectional area of the copper wire. This is not quite true, because the thickness of the insulating covering bears a greater ratio to the diameter of the wire for wires of small gauge than for wires of large gauge. In designing dynamos, moreover, one ought to be guided by the question of economy, not by the accident of there being only a certain volume left for winding. If there is insufficient space round the cores to wind on the amount of wire that economy dictates, new cores should be prepared having a sufficient length to receive the wire which is economically appropriate.

If no special limit of temperature-rise is prescribed, then the dominant consideration that governs the selection of the wire for winding is the amount of energy that may be wasted in magnetizing. If a temperature-limit is prescribed, then there must be provided a cooling-surface proportional to the energy that is wasted in the magnetizing coil. Experience shows that if the heating is not to exceed 20° to 25° (Cent.) above atmospheric temperature, at least 2½ square inches of external surface of coil must be allowed for each watt wasted by the coil's resistance. Or, conversely, if a bobbin has room for a coil of only a certain amount of surface, a winding must be chosen such that it will waste only one watt for each 2½ square inches of surface. Some useful rules have been given by Kapp[1] for preliminary calculations about depth of winding and weight of wire. Of course, these might be determined by first calculating the gauge of wire, bare and insulated, number of turns, turns per layer, and resistance per turn. If l is the length of wire, and D is the depth of winding, both in inches, and X the excitation in ampere turns, P the perimeter in inches of the coil, and W the weight of the coil in pounds, we have:

$$X = a\,l\sqrt{D}; \qquad [i.]$$

---

[1] See *Engineer*, April 1890.

where a is a coefficient which depends on the gauge of wire and thickness of its insulation. Also

$$W = \beta \frac{P}{l} \sqrt{\frac{X}{1000}}; \qquad [ii.]$$

where β is a second coefficient varying with the gauge of wire. These two formulæ are applicable to the case where a temperature-limit being imposed we allow 2½ square inches per watt. If no such limit is imposed and a given expenditure of energy is assumed, it is more convenient to replace them by following formulæ:

$$X = \gamma \sqrt{W\, l\, D \div P}; \qquad [iii.]$$

$$W = \delta \frac{P^2\, X^2}{1000000\, W}. \qquad [iv.]$$

The four numerical coefficients then have the following values:—

Diam. of Bare Wire in mils.	S.W.G.	a	β	γ	δ
40	19	522	0·495	820	0·195
120	10½	542	0·520	850	0·205
200	5½	570	0·615	900	0·246

For shunt coils the length, and therefore the volume, is dictated solely by reasons of economy. It is usual to allow 25 to 30 yards per volt.

Permissible Heating, and Surface of Emission.—In order that any coil may not over-heat it must have a sufficient surface, relatively to the amount of heat developed in it by the current. The Brush arc dynamo, 2 sq. inches of surface per watt lost, are allowed in the field-magnets, and 0·9 sq. inches in the armatures. In the Thomson-Houston armature 1·66 sq. inches. The relation between the heat developed, the surface of emission, and the resulting rise of temperature has been investigated by Forbes, Esson, and others. Forbes reckoned that heat would be emitted at the rate of $\frac{1}{800}$ of a watt[1] from 1 square centimetre if warmed 1° C. above the surrounding atmosphere. Esson, on the other hand, finds that for surfaces consisting of wire double cotton-covered and varnished the emission is much more rapid; and gives $\frac{1}{355}$ of a watt as the rate of emission per sq. cm. per degree (Cent.). Within the range of ordinary heating it may be assumed that the rate of emission is proportional to the excess of temperature over the surrounding air. The difference between Esson's rule and Forbes's is that Esson allows for the aid to cooling afforded by the brass bobbins and iron cores; whilst Forbes deals with heat emitted from the coil surface only.

Esson's rule, which appears to agree with the experience of various different makers, may then be stated

$$\theta° \text{ C.} = 355\frac{w}{s};$$

where θ stands for the rise of temperature, w is the watts expended in heat in the coil, and s its surface in sq. cms. Or, if Fahrenheit degrees and sq. inches are used, the rule becomes

$$\theta° \text{ F.} = 100\frac{w}{s}.$$

In using such rules, and calculating the watts developed in the coil (by multiplying the resistance by the square of the current), it must be remembered that the wire when warm has a higher resistance than when cold. A useful rule to take this into account is:—

To find resistance (*hot*) when resistance (cold) is known;

---

[1] The *watt* is the unit of rate of expenditure of energy, and is equal to ten million ergs per second, or to $\frac{1}{746}$ of a horse-power. A current of one ampere, flowing through a resistance of one ohm, spends energy in heating at the rate of one watt. One watt is equivalent to 0·24 calories per second, of heat. That is to say, the heat developed in one second, by expenditure of energy at the rate of one watt, would suffice to warm one gramme of water through 0·24 (Centigrade) degrees. As 252 calories are equal to one British lb. (Fahrenheit) unit of heat, it follows that heat emitted at the rate of one watt would suffice to warm 3·4 pounds of water one degree Fahrenheit in one hour; or one British unit of heat equals 1,058 watt seconds.

add to the known number of ohms 1 per cent. for every $2\frac{1}{2}$ Centigrade degrees, or for every $4\frac{1}{2}$ Fahrenheit degrees.

To find maximum permissible current, if the rise of temperature θ is prescribed as a limit.

$$\text{Max. permissible current} = \sqrt{\frac{\theta^\circ \text{ C} \times \text{sq. cm.}}{355 \times \text{resistance (hot)}}};$$

or

$$\text{Max. permissible current} = \sqrt{\frac{\theta^\circ \text{ F} \times \text{sq. inches}}{100 \times \text{resistance (hot)}}}.$$

Example.—A coil has 450 sq. in. of surface, and a resistance (hot) of 15 ohms. It is required to know what is the largest current it can carry continuously without heating more than 30° F. above the surrounding air. Here the maximum current will be 3 amperes.

If we assume that a safe limit of temperature is 90° F. (or 50° C.) higher than the surrounding air, then the largest current which may be used with a given electromagnet is expressed by the formula:—

$$\text{Highest permissible amperes} = 0{\cdot}95 \sqrt{\frac{s}{r}},$$

where s is the number of square inches of surface of the coils and r their resistance in ohms.

Similarly, for *shunt coils* we have:—

$$\text{Highest permissible volts} = 0{\cdot}95 \sqrt{s\,r}.$$

The magnetizing power of a shunt coil, supplied at a given number of volts of pressure, is independent of its length, and depends only on its gauge, but the longer the wire the *less* will be the heat waste. On the contrary, when the condition of supply is with a constant number of amperes of current, the magnetizing power of a coil is independent of the gauge of the wire, and depends only on its length; but the larger the gauge the less will be the heat waste.

Owing to the cooling effect of the air-currents while running, it is found that when a dynamo is stopped at the end of a long run, the surface temperature immediately rises above what it was when running, as the heat which is being conducted outwards from the hotter interior is not now so rapidly got rid of. In the Admiralty specifications it is laid down that after the end of a long run of six hours, no part of the machine shall at the end of one minute after stopping show a greater rise than 11° C. (= 20° F.) above the surrounding air. This is absurdly low; and for ordinary engine-room work a rise three or four times as great is perfectly safe. Kapp allows 1·5 sq. in. (= 9·7 sq. cm.) for each watt lost in the armature; and 2·5 sq. in. (= 16·2 sq. cm.) per watt in the field-magnet. Esson finds that on armatures running at ordinary speeds, there will be a rise of 35° C. if for every watt wasted in heating 1·13 sq. in. (= 7·3 sq. cm.) be allowed. The formula given above for field-magnets would show for the same rise a minimum surface of 1·5 sq. in. (= 9·7 sq. cm.) per watt. Esson finds an approximate rule for different speeds to be :—

$$\theta^\circ\ (\mathrm{C.}) = \frac{55\,w}{s\,(1 + 0{\cdot}00018\,v)};$$

where s is given in square inches, and v is the peripheral velocity in feet per second. If these are given in square centimetres, and metres per second, respectively, the rule becomes :—

$$\theta^\circ\ (\mathrm{C.}) = \frac{354\,w}{s\,(1 + 0{\cdot}0006\,v)}.$$

Some calculations about the greater heating of interior layers have been given by Mr. Joyce.[1]

The following rules are useful for calculating the windings for machines of same type, but of varying size, or output.

To reach the same limiting temperature with equal-sized bobbins wound with different-sized wire, the cross-section of the wire must vary as the current it is to carry; or in other words, the current density (amperes per square centimetre) must remain constant.

To raise to the same temperature two similarly shaped coils, differing in size only, and having the gauge of the wire in the same ratio (so that there are the same number of turns on the large coils as on the small one), the currents must be such that the squares of the currents are proportional to the cubes of the linear dimensions.

---

[1] *Journ. Inst. Electr. Engineers*, xix. 248, 1890.

Similar iron cores, similarly wound with lengths of wire proportional to the squares of their linear dimensions, will, when excited with equal currents, produce equal magnetic forces at points similarly situated with respect to them. (Sir W. Thomson, *Phil. Trans.*, 1856, p. 287.)

Similar machines must have ampere-turns proportional to the linear dimensions, if they are to be magnetized up to an equal degree of saturation. (J. & E. Hopkinson, *Phil. Trans.*, 1886, p. 338.)

If two machines are to give same electromotive-force, the diameter of the wire of the coils must vary as the linear dimensions.

If, in altering the field-magnets of a machine of any given capacity, the lengths of the several portions of the magnetic circuit remain the same, but the several areas are altered, then the wire for rewinding must have its cross-sectional area altered in proportion to the periphery of the section of the cores.

The resistance of a coil, the volume of which is known, and which is wound with (round) copper wire of diameter d millimetres, enlarged by insulation to a diameter of D millimetres, can be calculated by the following rule, which is based on the assumption that the partial bedding of the convolutions allows of 10 per cent. more wires being got in than would be the case if they were exactly wound in square order. This figure can only be approximate, as the amount of bedding varies somewhat with the relative thickness and pliability of the coating of insulating materials, as well as with the gauge of the wire. If v be the volume in cubic centimetres, the resistance r of the coil in ohms (cold) will be

$$r = 0{\cdot}0244 \, \frac{v}{\mathrm{D}^2 \, d^2}.$$

If v be expressed in cubic inches, and D and d in mils. (1 mil = ·001 inch), then the approximate formula becomes

$$r = 960{,}700 \frac{v}{D^2 d^2}.$$

LENGTH AND DIAMETER OF ARMATURES.

Various rules have been given for the ratio between the length of an armature and its diameter, embodying the results of practice.

In the case of two-pole dynamos the usual dimensions for ring armatures vary from $L = \frac{1}{2} d$ to $L = 1\frac{1}{2} d$; $L = d$ being frequent. The symbols here refer to measurements on the unwound core. For drums $L = 2\,d$ is frequent, though the values $L = 1\frac{1}{2}\,d$ and $L = 3\,d$ are also found.

SECTION OF FIELD-MAGNETS.

Comparison of the machines of various makers shows that for ring machines the usual practice is to allow for magnet-cores of ring machines a cross section 1·66 times that of the armature core, if of wrought iron; or 3 times, if the magnet core is of cast iron. For the magnet-cores of drum machines the usual figures are 1·25 and 2·3.

The question sometimes arises what is the best *shape* of section to give to magnet-cores. This point is readily answered by considering the geometrical fact that of all possible forms enclosing equal area the one with least periphery is the circle. For facilitating comparison, the following table exhibits the relative lengths of wire required to wind round various forms of section enclosing equal area; the area of the simple circular form being taken as unity, and allowance made for thickness of winding.

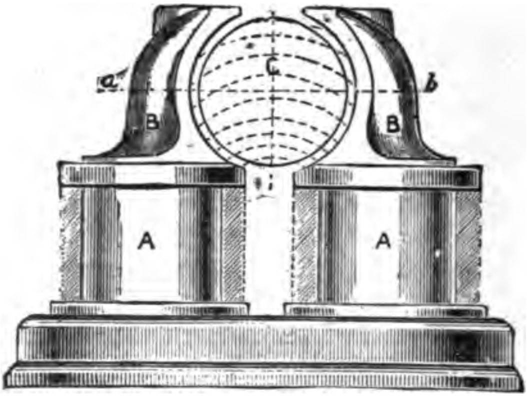
Circle	3·54
Square	4·00
Rectangle, 2 : 1	4·24
Rectangle, 3 : 1	4·62
Rectangle, 10 : 1	6·91
Oblong made of one square between two semicircles	3·76
Oblong made of two squares between two semicircles	4·28
Two circles side by side	4·997

Two circles, but wire wound round both together	4·10
Three circles „ „ „ „ each separately	6·13
Four circles „ „ „ „ „ „ „	7·09

SYMMETRY OF FIELD-MAGNETS.

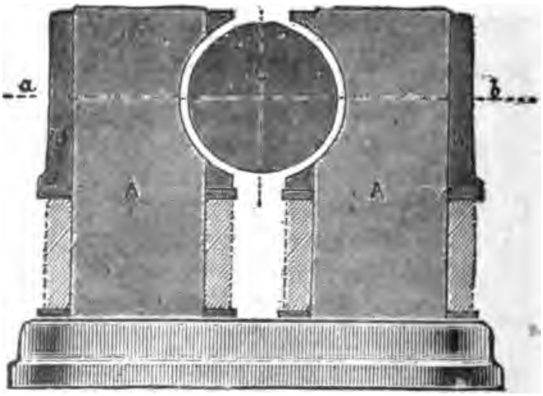
It was pointed out on p. 206, that in two-pole single-circuit field-magnets the field is unsymmetrical, being much stronger between the inner horns than between the outer horns of the pole-pieces, if the poles are shaped away as in Fig. 120, No. 23.

FIG. 284.



OLD FIELD-MAGNET OF THE ALSACIAN COMPANY.

FIG. 285



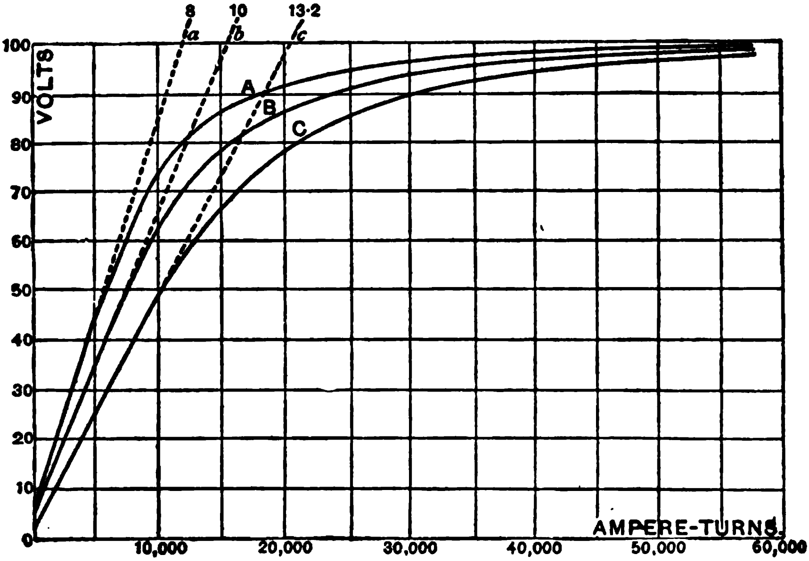
NEW FIELD-MAGNET OF THE ALSACIAN COMPANY.

This produces several evil results. Firstly, the armature is attracted downwards as a whole (see p. 387); secondly, the armature, if ring-wound will be electrically out of balance, owing to the unequal magnetic fields at opposite ends of a diameter; thirdly, the neutral points for non-sparking will not be at opposite ends of a diameter. Fig. 284 depicts a 60-kilowatt dynamo of the Alsacian Company which had these defects, and was replaced by the more massive form shown in Fig. 285, having cast-iron polar caps that slip on over wrought-iron cores.

EFFECT OF WIDENING THE GAP-SPACE.

The effect of widening the gap-space is in every case to cause a larger amount of energy to be spent in maintaining the magnetic field across the gap. Or, in other words, more ampere turns are required on the field-magnet. It also has some other results. It slightly increases the leakage coef-

FIG. 286.



CHARACTERISTICS WITH DIFFERENT GAP-SPACES.

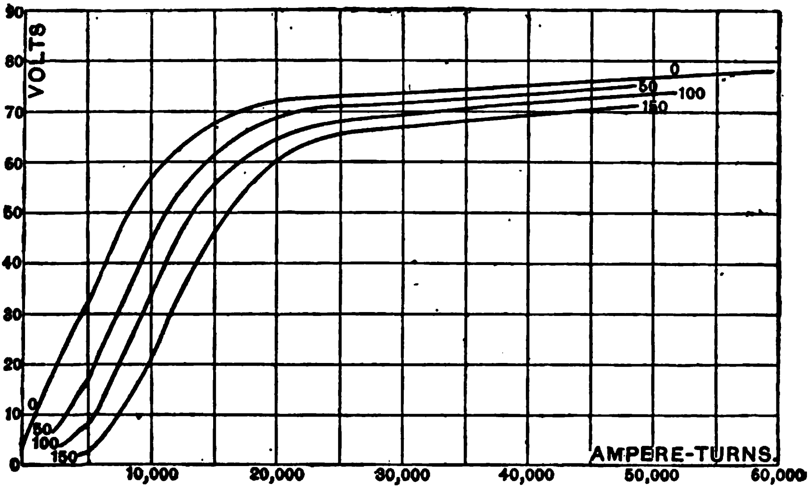
ficient *v*. It enables more copper or thicker conductors to be wound on the armature, diminishing its internal resistance; and, if the armature has not been loaded beyond the safe point of sparklessness, increases the output of the machine. It has the further not unimportant result of increasing the reluctance in the path of the cross-magnetizing magnetomotive forces, and diminishes their prejudicial action. Some ideas as to the first of these effects may be gathered from considering the characteristic curves given by Arnoux, in Fig. 286, showing the result of widening a gap-space from 8 to 10, and then to 13·2 millimetres. Here we find that the initial slopes of the characteristic right are given by lines whose tangents are inversely proportional to the gaps: for the heights *c d*, *b d*, and *a d*, are inversely proportional to the numbers given as the widths of the gap-spaces. It will be noted that for the upper part of the characteristic the three lines approach one another. Obviously the suggestion that the intensity of field of a dynamo is in inverse ratio to the gap-space does not hold for dynamos at the working degree of excitation.

INTERFERENCE OF ARMATURE FIELD.

As explained in Chapter IV., p. 76, the armature-current tends to cross-magnetize, and, if the brushes have a forward lead (or in a motor a backward lead) tends also to demagnetize the field. We saw on p. 87 that the position of the neutral point for non-sparking is affected by this interference; and on p. 285 we learned how to compensate the demagnetizing effect. We have now to consider the matter further from the point of view of dynamo design.

In the first place, let us examine the behaviour of some existing dynamo, by observing the relation between its voltage and the amount of excitation, at some constant speed, under varying conditions of load. Let the lead given to the brushes be varied as required to fulfil the condition of sparklessness. First let a curve be found with zero armature current; then with a 50 ampere load, then with 100 amperes, and so forth. The experiments should be made in each case by beginning with the highest excitation (and smallest angle of lead) and gradually diminishing the excitation (and increasing the lead) until a sparkless position can no longer be found for the brushes. This dynamo[1] was intended for a normal output of 150 amperes at 70 volts. It will be found that in each case, the smaller the load the more may the excitation of the field be diminished before the state of things is reached that no neutral point can be found. In other words, there will always be some definite relation between the ampere-turns on the armature, and those on the field-magnet which fixes the working limit of sparklessness. We shall presently enquire into this relation. For the present it may be remarked that these load-curves[2] give us much information as to the necessary windings of the field-magnet,

FIG. 287.



LOAD-CURVES OF A DYNAMO.

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[1] See Arnoux in *Bull. de la Soc. Int. des Electriciens*, vi. 61, 1889.

[2] For other examples of load-curves see Esson in *Journal Instit. Electrical Engineers*, xix. 152, 1890; and Kapp in *Proc. Instit. Civil Engineers*, Feb. 1889.

how many ampere-turns must be contributed on open circuit by the shunt coil, and how many compensating ampere-turns must be added by the series coil in order to keep up the voltage.

LIMITS OF LOAD AND NON-SPARKING POINT.

Two things limit the output of a dynamo: the heating of its armature conductors, and sparking at the brushes. Given a dynamo, if by widening the gap a little and rewinding its armature with copper wire of double cross-section, we reduce its resistance to one half, we may then take from it a double current with no more heating than before, provided it still does not spark. Such a reconstituted machine of double output would clearly cost less than two of the previous pattern. But the limit of such an augmentation of the output by increasing the ampere-turns on the armature is reached very soon; for the cross-magnetizing tendency is doubled, and the lead increased, and the demagnetizing tendency more than doubled by doubling the ampere-turns of the armature. These perturbing effects may be all included under the general name of *interference* used in the previous paragraph: they have been investigated more or less fully by Hopkinson,[1] and more completely by Swinburne[2] and by Esson,[3] whose results mainly occupy the remainder of this chapter.

It has been pointed out, on p. 84, that because the individual sections of the armature winding possess self-induction, the reversal of the current in them in the act of commutation as they pass the brush requires the presence of an impressed electromotive-force; and that this is accomplished by giving the brush a lead (forward in a dynamo, backward in a motor) so that that section in which the current is to be reversed is at that time passing through the fringe of the magnetic field. The stronger the current to be reversed, the stronger is the field necessary for sparkless reversal. But the field under the "trailing" horn of the pole-piece (or in a motor, the "leading" horn), near which commutation must take place is, as we have seen (Figs. 63 and 67), weakened by the interference of the armature. Now the cross-magnetizing action of the armature tends to send magnetic lines up (see usual diagram Fig. 62, p. 78) both sides of the ring core, which tend to cross the gaps and return through the masses of the pole-pieces; the strongest cross-magnetizing force in the gaps being under the tips of the polar horns. This cross action opposes the normal flux of magnetic at the top right and bottom left corners (of Fig. 63), and helps it at the other two. The cross-magnetizing magnetomotive-force under the pole-tips (assuming the gaps alone to offer any appreciable reluctance) is equal to $\frac{4}{10}\pi$ times the ampere-turns of all the conductors that lie in the gaps, or within the angle of polar span Ψ. Using the usual symbols—C for the number of conductors around the armature, and i_a for total armature currents—we have for the total ampere-turns on the armature $\frac{1}{2}\,C \times \frac{1}{2}\,i_a$, of which $\Psi \div 180°$ are effective, and of which the half may be taken as the part operative in either place where the cross-circuit crosses a gap. If Ψ is taken at 120°, the cross-force under the tip will be

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[1] *Philosophical Transactions*, 1886, pt. i., p. 331; and *Electrician*, xviii., Dec., 1886.

[2] *Journal Instit. Electrical Engineers*, xv., 540, 1886; and xix., 90 and 265, 1890.

[3] *Ibid.*, xix. 118, 1890; and xx. 265, 1891; also *Electrical World*, xv. 213, 1890. See also *Electrical Review*, series of articles on Synthetic Study of Dynamos, 1890.

$$\tfrac{1}{2}\,C \times \tfrac{1}{2}\,i_a \times \tfrac{1}{2} \times \tfrac{4}{10}\,\pi \times \tfrac{120}{180} = C\,i_a \times 0{\cdot}104\,;$$

or equals the ampere-turns[1] on the armature multiplied by 0·416. Now let us see what number of ampere-turns on the armature would produce a cross-force in the gap just exactly balancing the normal magnetizing force there, so as to neutralize the field under the pole-tip. In that case sparkless reversal would be impossible, and so we should have ascertained the limit of load. Now the difference of magnetic potential in the gap (or that part of the magnetomotive-force that is spent therein) is equal to the product of the magnetic reluctance of the gap into the flux across it. If l_2 be the length across the gap and A_2 the polar area, the reluctance of the gap is $l_2 \div A_2$, and the magnetic potential difference in it is $= \mathbf{N}\ l_2 \div A_2$. Now call the length of the armature core or of the pole-face, parallel to the axis, L; the breadth of the pole-face measured along the curve from tip to tip b; the radial depth of the core r; and its sectional area A_1. We may assume that in the core the magnetization is pushed to $\mathbf{B} = 17{,}000$. Then we have the following relations:—

---

[1] This term is here used precisely as for any electromagnet. In two-pole drum-armatures it is half the armature current multiplied by half the number of external conductors. In multipolar machines (wound with parallel grouping) it is equal to total current multiplied by total number of conductors and divided by the square of the number of poles. In Esson's paper of 1890 (*Journal I. E. E.*, xix. 143), the term ampere-turns was used in a different sense, namely, as the product of the total number of conductors into the current carried by each. This is the same thing to which in his paper of 1891 (*Journal I. E. E.*, xx. 266) he gave the not very apposite name of "volume," but which would have been better described as the total circulation of armature current. The name used here for this quantity is the *circumflux*. For two-pole machines the circumflux is twice the ampere-turns; for four-pole machines, four times, &c.

$$\mathbf{N} = 17000\ A_1;\ A_1 = r\ L;\ A_2 = b\ L.$$

Substituting these in the preceding expression, and cancelling out L, we get—

$$\text{Magnetic potential in gap} = 17000 \times r \times l_2 \div b.$$

Equating this to the cross-force we get—

$$\frac{Ci}{4} = \frac{40900\ rl_2}{b}.$$

For some purposes it is more convenient—particularly in relation to multipolar machines—to consider not the ampere-turns of the armature, but the effective circulation of current as reckoned by multiplying together the number of armature conductors and the current carried by each independently of its direction. This quantity, here denoted by the symbol Q, we shall call the *circumflux*.[1] It is equal to the product of the whole armature current, into the whole number of armature conductors, divided by the number of poles. For a two-pole dynamo we then have as the limiting load on the armature:—

$$Q = \frac{Ci_a}{2} = \frac{81800\ r\ l_2}{b}.$$

---

[1] Called by Esson at one time the "ampere-turns," and later the "volume" of the armature current. See preceding foot-note.

Esson,[1] gives the result of observation of a number of modern dynamos by different makers, and found the actual numerical coefficient to vary from 61265 to 95905 for ring machines, with a mean of 85000, differing little from the theoretical 81800 given above.

From the foregoing it appears that the maximum load which an armature can carry, within the limit of sparklessness, is directly proportional to the radial depth of core, and to the length of the gap, but inversely proportional to the breadth of the polar span. If, therefore, taking an existing machine whose load is just within the spark limit, we wish to make it carry a heavier load (or more copper on the armature) we may do so either by increasing the radial depth of the core-disks, or by increasing the gap-space (whether wanted for copper and clearance or not), or lastly, by diminishing the breadth of span of the polar faces. The first of these causes means a new armature; the second requires the pole-faces to be bored out afresh, and also means some (not large) addition to the magnetizing power of the field-magnet; the third has the effect of concentrating the magnetic flux, therefore, lowering slightly the permeability, and necessitating either a slightly higher speed or a slight increase in the magnetizing power.

The circumflux or polar circulation of armature current permissible for an armature of given diameter may be given in terms of the diameter by assuming (for ring two-pole armatures) that $b = 1{\cdot}05\ d$; $r = 0{\cdot}1 d$; and $l_1 = 0{\cdot}05\ d$.

Substituting these values, we get

$$Q = 390\ d.$$

Esson takes 400 d (centimetres) as the limiting value of Q, for rings, and 600 d as the value for drums. Kapp allows 1000 ampere-turns (or 2000 circumflux in case of two-pole machine) for each inch of diameter above 12 inches, as a safe load.

We are now ready to consider the safe output (watts) of a dynamo in terms of its dimensions.

---

[1] *Journal I. E. E.*, xx. 142, 1890.

The gross output of a bipolar dynamo is—

$$W = E i_a = n \mathbf{N} C i_a \div 10^8, \qquad \text{(see p. 211)}$$

or for a multipolar dynamo

$$W = n \mathbf{N} \frac{C i_a}{p} \div 10^{\circ};$$

where p stands for the number of *pairs* of poles: so that the value of Q, the circumflux of armature current, will be $C i_a \div 2 p$; whence

$$W = 2n \mathbf{N} \times Q \div 10^8. \qquad [\alpha]$$

Now assume (as fair average of actual cases) that pole-pieces together cover $\frac{7}{10}$ of circumference (or $2{\cdot}2 \times d$), and that the value of **B** in the gap is 5000. Then, if L is length of armature core (cms.), the working area of the armature through which magnetic lines go in or out $= 2{\cdot}2 \times d \times L$; whence area of any one polar part is $2{\cdot}2\, d \times L \div 2\, p$, and the flux of magnetic lines through any one pole will be 5000 times this; or for the total flux through the $2\, p$ poles will be

$$\mathbf{N} = p \times 5000 \times 2{\cdot}2\, d \times L \div 2\, p = 5500\, d \times L.$$

Inserting this value we have—

$$W = 11000 \times d \times L \times n \times Q \div 10^8 \qquad [\beta]$$

But, according to Esson, as above, $Q = 400\, d$ for rings, or $600\, d$ for drums, as the safe loads. Inserting these values we get—[1]

$$\left\{ \begin{array}{l} \text{for rings } W = d^2\, L\, n \times 0{\cdot}044 \\ \text{for drums } W = d^2\, L\, n \times 0{\cdot}066 \end{array} \right\} \qquad [\gamma]$$

Now d^2 L is proportional to the volume of the armature core. Hence we conclude that the output is proportional to volume and to speed, and is independent of the number of poles and of the grouping of the armature conductors. Kapp finds it (for equal surface temperature) to increase as the 3½ power of the diameter, which is slightly higher than the volume, probably because of the somewhat higher peripheral speeds attained by large armatures.

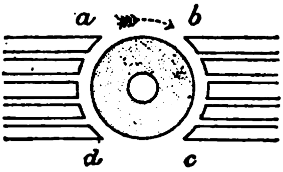
---

[1] Esson, taking slightly greater width of pole-pieces, gets 0·048 and 0·072 as the respective co-efficients. Snell (*Journal I. E. E.*, xx. 197) finds his machines give as their co-efficients, when translated into centimetres and seconds to correspond, 0·0375 and 0·056 respectively.

DEVICES FOR CHECKING SPARKING.

Seeing that the cross induction is responsible for the weakening of the field needed for reversing the current at commutation, various devices have been suggested for checking the evil. One is to apply an auxiliary reversing pole.[1] Another, applicable to field-magnets with double circuit (such as Nos. 8 and 24 of Fig. 119), is to make a deep nick between the right and left-hand halves, and so throttle the cross-flow of magnetic lines. Another suggestion, made by the author of this work some years ago, was to construct the field-magnets of pieces of iron, with longitudinal gaps, as in Fig. 288. Another suggestion, by Mr. Sayers, is to notch the pole surface, near the pole-tip, with a deep notch, so as to concentrate the field, and supply a "fringe" suitable for reversing.

FIG. 288.



DESIGN OF MULTIPOLAR DYNAMOS.

The advantage of using Q (the circumflux) rather than the ampere-turns, in the foregoing investigation, is that the spark limit of load depends not on the total ampere-turns or action of the whole armature as an electromagnet, but on the circulation of current per pole. Hence the results obtained are available immediately for multipolar as well as bipolar machines, as was pointed out by Esson, to whom is due the credit of this conception.

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[1] See Swinburne (*Journal I.E.E.*, xxx. 105, 1890), and Housman (*ib.*, xx. 239, 1891), who maintains that if B = 7000 under the pole-piece, the auxiliary field for reversing must be at least = 3000.

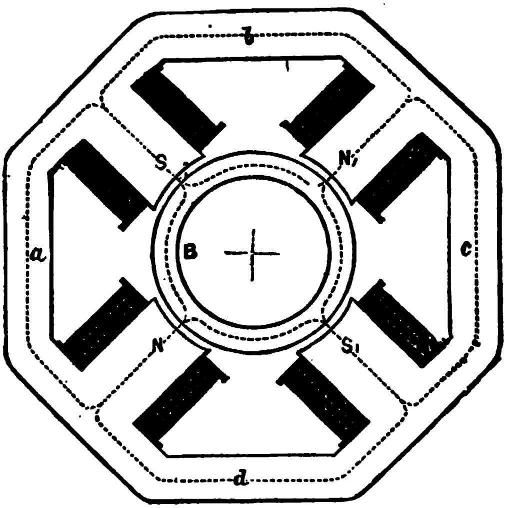
The formula at the foot of p. 438 may now be re-written—

$$Q = \frac{277 \, B \, l_2}{\psi};$$

where B is the strength of field in the gap-space.

If we assume the limiting values of Q, and the usual value of B as already determined, then if ψ, the angle of polar span, be taken at 130° it follows that the radial depth l_2 of the gap-space must not be less than $\frac{1}{28} d$ for rings, nor less than $\frac{1}{18} d$ for drums. Then, if in order to make a large output machine, whilst keeping to two poles, we increase d, we must either increase l_2 or B, or else diminish ψ or perform some combination of these processes, which in any case involves a greater expenditure of power in maintaining the field in the gap-space. Herein lies the advantage of multipolar construction for large outputs. Consider such a form as Fig. 289 with four poles. To prevent undue leakage from pole

Fig. 289.



Four-pole Ring Dynamo (Brown).

to pole the distance between pole horns is wider relatively to the polar span than in a two-pole machine; and, for an equally high value of **B** in the gap-spaces, the section of the ring is reduced, its diameter enlarged, and with its diameter its cooling surface. For drum-wound machines there is, in addition to such gains, the additional advantages that end-connexions are much simpler, and ventilation easier, than for two-pole machines. But does it pay the constructor to make the change? There is a little more labour in tooling castings; but will he save copper? A case will show that, beyond a certain limit of size, there is a saving. Consider a two-pole drum; $d = 50$; $L = 90$; $\mathbf{B} = 5000$ in the gap; $\psi = 130°$. Then it will not be sparkless unless the gap-space l_2 is at least 3·2 cm., or about 0·9 cm. more than is needed for windings and clearance. If, to make this work sparklessly, we diminish the gap and increase **B** to 7,000, or diminish ψ to 100°, we still gain nothing in magnetizing power. Now substitute a four-pole drum: $d = 84$; $L = 45$; $\mathbf{B} = 5000$. With this increased diameter, the gap-space may be reduced to a minimum, and the magnetizing power may be reduced by at least 30 per cent., and the total weight of iron by nearly 40 per cent., which will more than pay for the extra labour of tooling. Esson states that the cost of a four-pole dynamo, of output W at speed n, may be put as being equal to that of two dynamos, each of output $\frac{1}{2}$ W at speed $2\,n$, and so forth. The cost of field-magnet castings is reduced, and their weight lessened, when, as in the large machines of Siemens and Halske (Plate XI.) the ring is of such large dimensions that the field-magnet can be placed internally.

For large output machines, multipolar forms are, then, preferable to bipolar; firstly, because they give their maximum sparkless output with minimum clearance, and therefore with minimum weight of copper on magnet; secondly, because they keep cooler, so that for a given volume of core and winding there is actually a greater output. Snell compared a four-pole drum machine of 60 cm. diameter with a two-pole drum of same diameter—the one giving

300 amperes at 250 volts, the other 70 amperes at 700 volts, or only about ⅔ the output. Multipolar machines have one further advantage over two-pole machines, in that their length may be varied relatively to the diameter without much loss in economy. In the case of drum windings this is very marked. For two-pole drums the best proportion is $L = 3{\cdot}3\ d$, and if $L = 2\ d$ there is an increase of 5 per cent. in the copper used, or if $L = 1\frac{1}{2}\ d$ the increase is over 10 per cent., whereas for four-pole drums $L = \frac{1}{2}\ d$, uses same copper as $L = 2\ d$; and for a six-pole drum $L = \frac{1}{4}\ d$ is just as good.

BEST THICKNESS OF GAP-SPACE.

Professors Ayrton and Perry have investigated[1] the rule for the best thickness of the conductors on armatures. Using the same notation as in the rest of this book, their argument is as follows:—The power developed by the armature may be written

$$w = E\ i_a = \frac{n\ C\ N}{10}\, i_a;$$

or writing a for the number of amperes per square centimetre in the cross-section of the armature, r for the external radius of armature core, and t for thickness of external winding on armature,

$$C\ i_a = 2\ a \times 2\ \pi\ r\ t;$$

whence

$$w = \frac{4\ \pi\ r\ n\ N.\ t\,a.}{10^8}$$

Now, writing p as the resistance of the armature winding per centimetre cube (including copper and insulation), the watts wasted per cubic centimetre in heating will be $= p$; and the watts wasted in heating the external conductors on the armature will be $= 2\ \pi\ r\ t\ l\ p\ a^2$; where l is the length of the external conductors on the armature. Now let the rise of temperature above that of the surrounding air be called θ (degrees C.), and let z stand for the amount of heat (expressed in watts) emitted per square centimetre of surface, for an excess of temperature 1° C. above the surrounding air. Then the watts emitted as heat from the whole external surface of the armature will be $= z\,\theta\,2\,\pi\,r\,l$. Equating the watts generated and the watts emitted at the surface, we have

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[1] See their paper, *Phil. Mag.* for June 1888.

$$2\,\pi\,r\,t\,l\,\rho\,a^2 = z\,\theta\,2\,\pi\,r\,l,$$
$$t\,\rho\,a^2 = z\,\theta,$$
$$t\,a^2 = \frac{r\,\theta}{\rho}.$$

Now write a_1, θ_1, w_1, and N_1, as the highest permissible values of a, θ, w, and N respectively. And write q for $\sqrt{z\,\theta_1/\rho}$. It appears that the value of q in the best modern machines is about 288. Now $t\,a = q\sqrt{t}$. Inserting this value, we get

$$w_1 = \frac{4\,\pi\,r\,n}{10^8}\,\mathrm{N}_1\,q\sqrt{t}.$$

Now by the principle of the magnetic circuit, p. 177, we have

$$\mathrm{N} = \frac{4\,\pi\,\mathrm{S}\,i/10}{\frac{2\,(d+t)}{\mathrm{A}_2} + \Sigma\,\frac{l\,v}{\mathrm{A}\,\mu}};$$

where d is the clearance between the surface of the armature windings and the curved face of the polar surface of the magnet, A_2 the effective area of the polar surface, and $\Sigma\frac{l\,v}{\mathrm{A}\,\mu}$ the magnetic reluctance of the iron parts of the magnetic circuit. Assume that N is worked up to its highest permissible value N_1, then we may write

$$w_1 = \frac{4\,\pi\,r\,n\,q}{10^8}\sqrt{t}\,\frac{4\,\pi\,\mathrm{S}\,i/10}{\frac{2\,(d+t)}{\mathrm{A}} + \Sigma\,\frac{l\,v}{\mathrm{A}\,\mu}}.$$

This expression varies in value when the value given to t is varied, and it can be shown to have a maximum when the value of t is such that

$$\frac{2\,t}{\mathrm{A}_2} = \frac{2\,d}{\mathrm{A}_2} + \Sigma\,\frac{l\,v}{\mathrm{A}\,\mu}.$$

That is to say, the permissible continuous output of the machine is a maximum when the thickness of the winding on the armature is such that *the magnetic reluctance of the space occupied by the winding on the armature is equal to the reluctance of the rest of the magnetic circuit.*

Assuming that practically the whole of the gap-space between armature core and pole-piece is filled with armature winding, the above rule amounts to saying that, given the construction of armature, the dynamo ought to be worked at such a degree of excitation that its total magnetic reluctance is run up to be twice as great as that of the gap-space alone. This is indeed no other than the diacritical stage of magnetization, the permeability in gross of the magnetic circuit—iron and air together—being at this point reduced to half its initial value. But we see from the researches of Swinburne and Esson that to prevent sparking a wider gap-space is necessary than that occupied by copper and clearance.

Plate i

APP DYN FIELD MAGNET

AMPERES AT 8.

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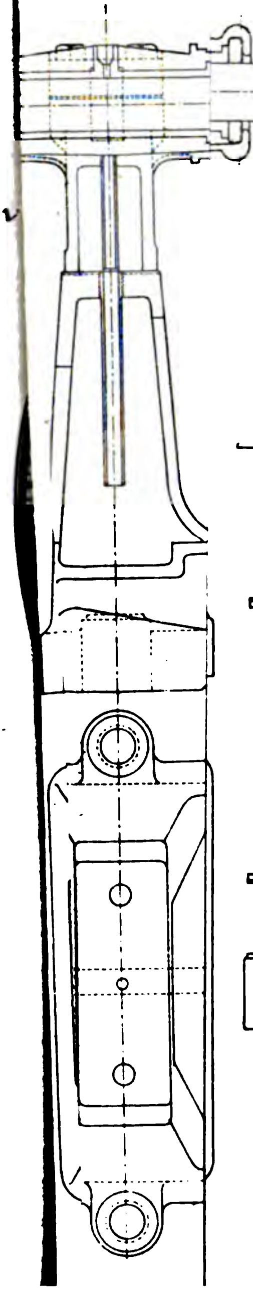

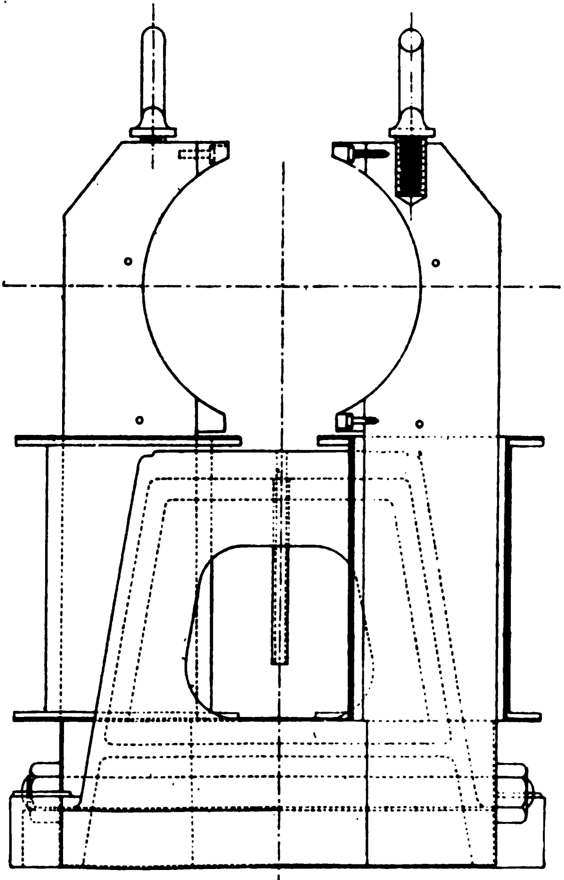

FIG 3

Plate ii

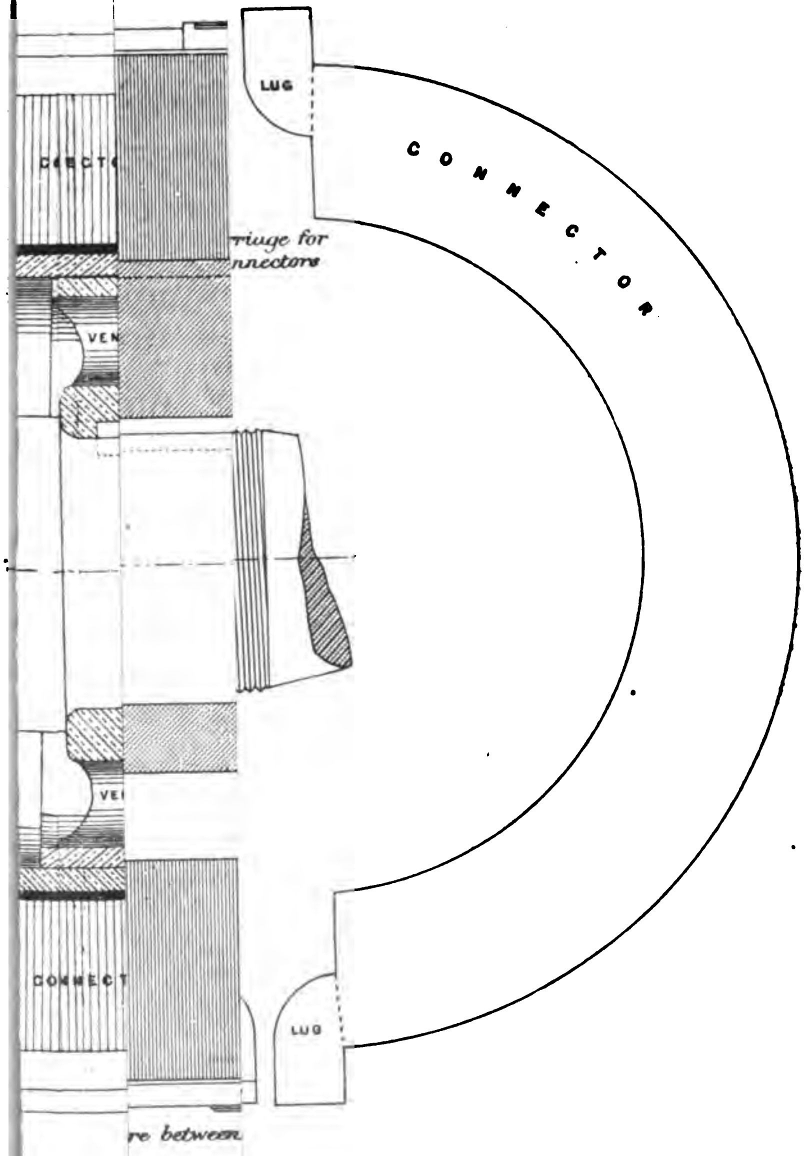
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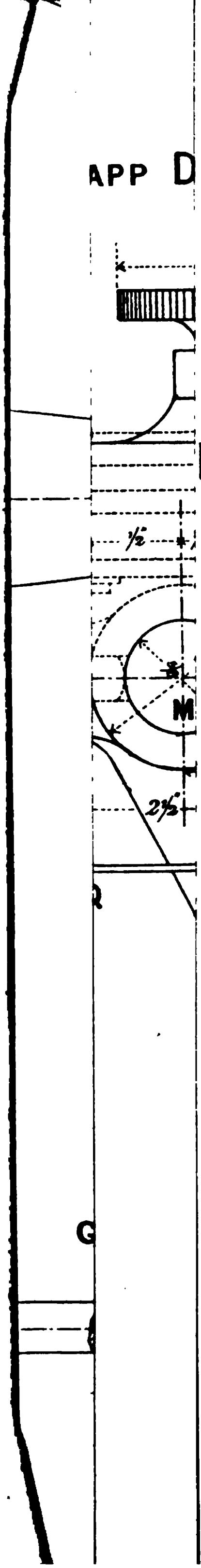
Plate iii



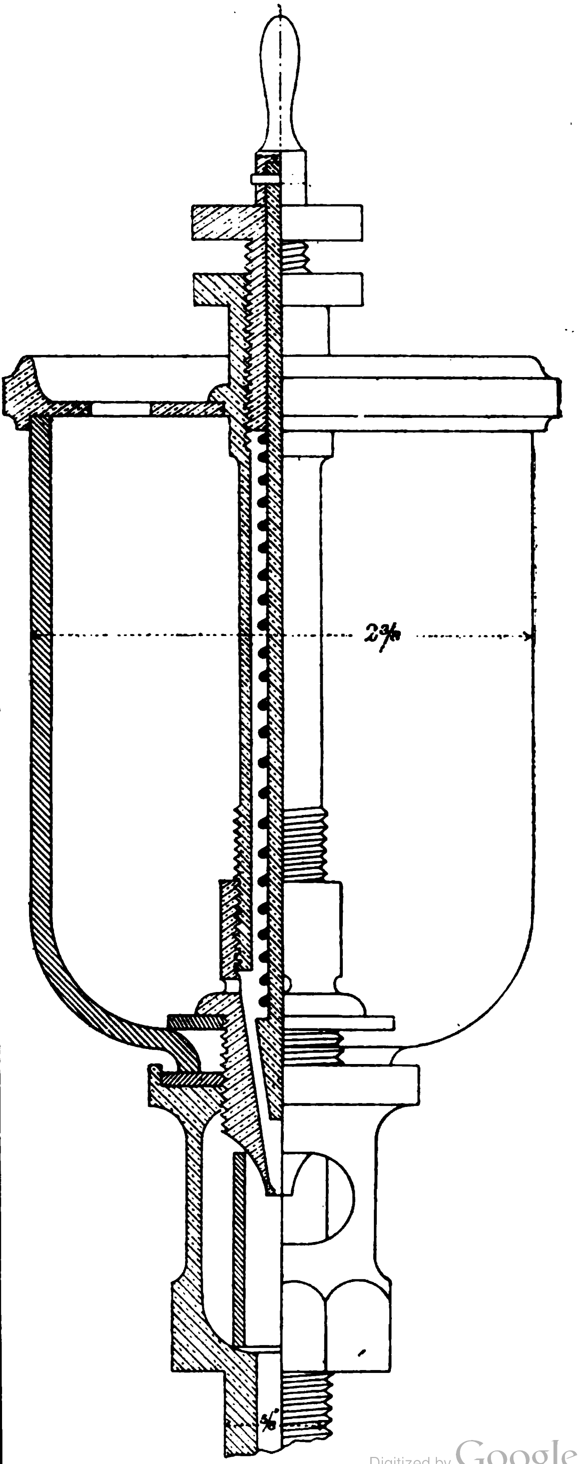


Plate iv

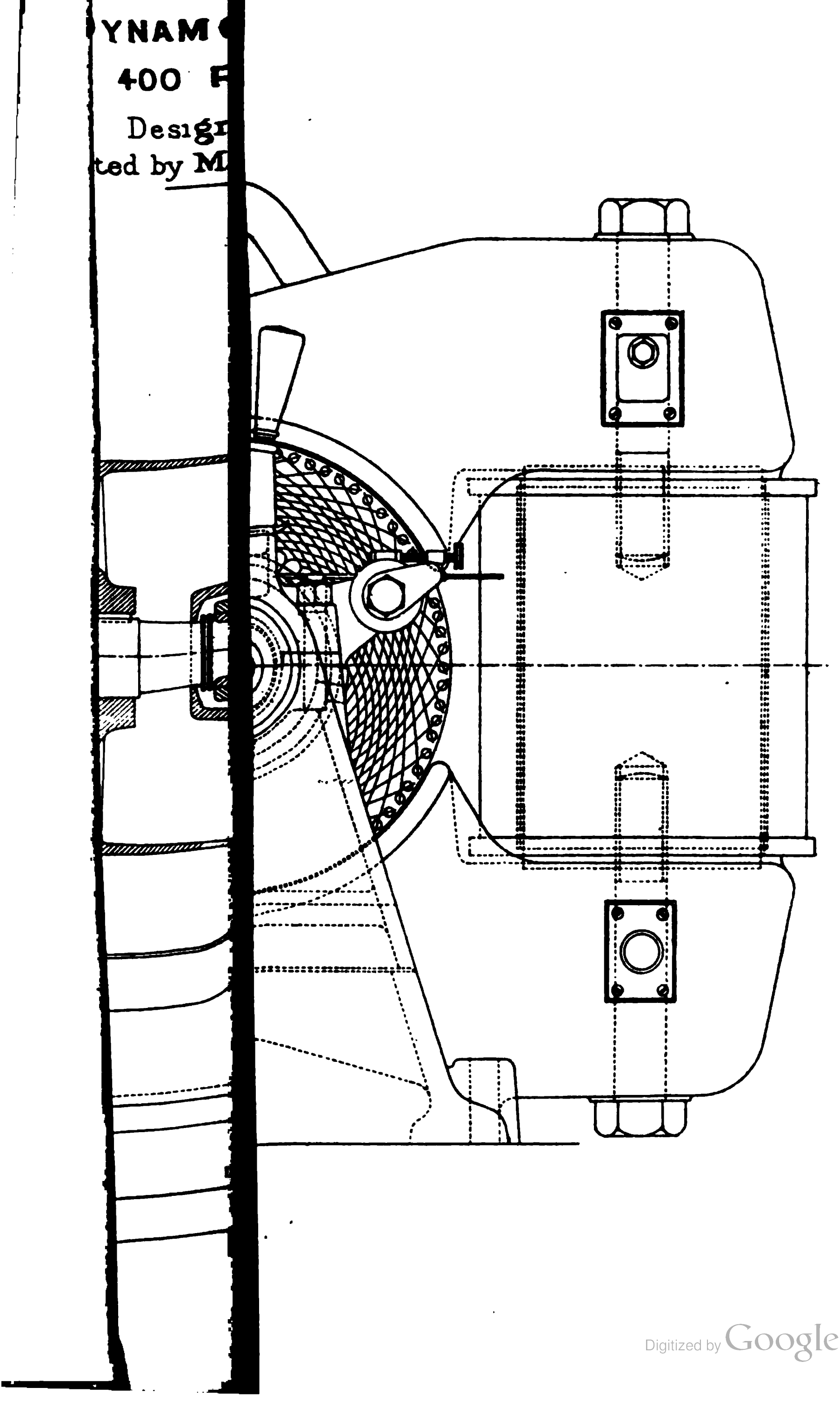


Plate v

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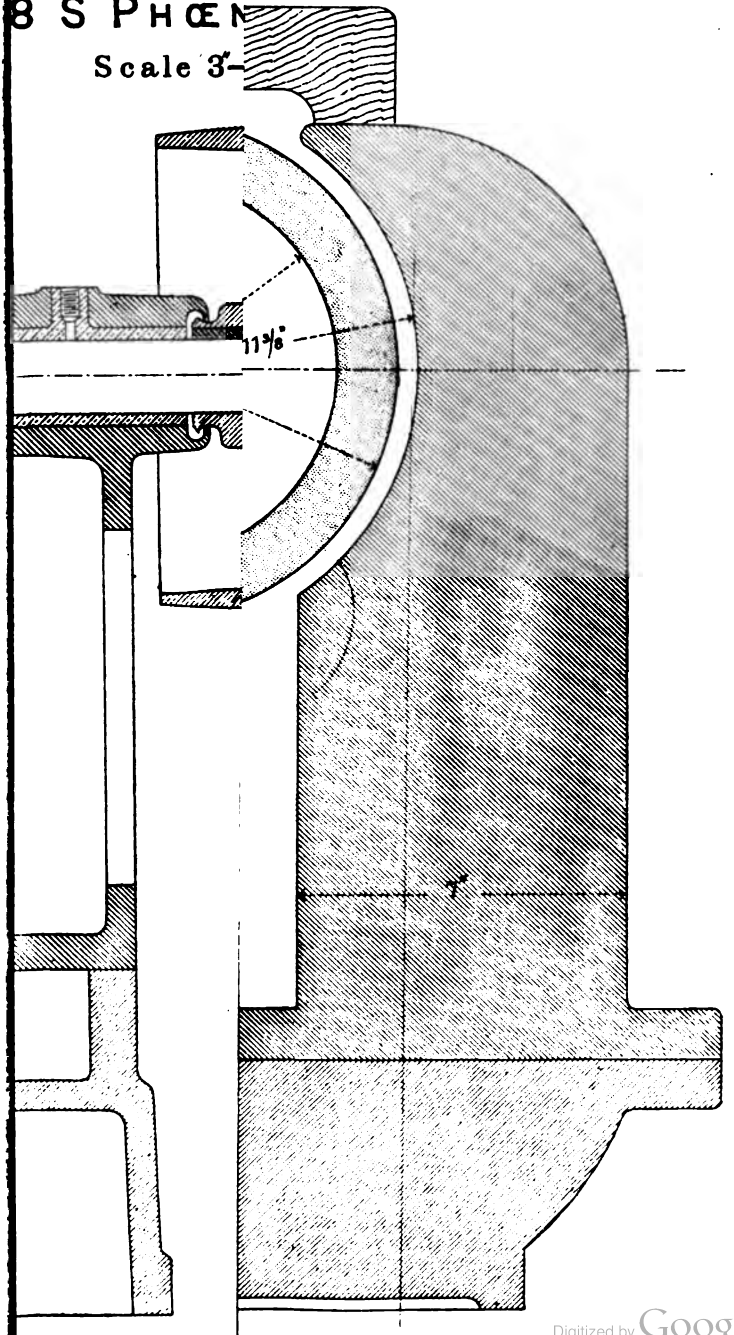

Plate vi

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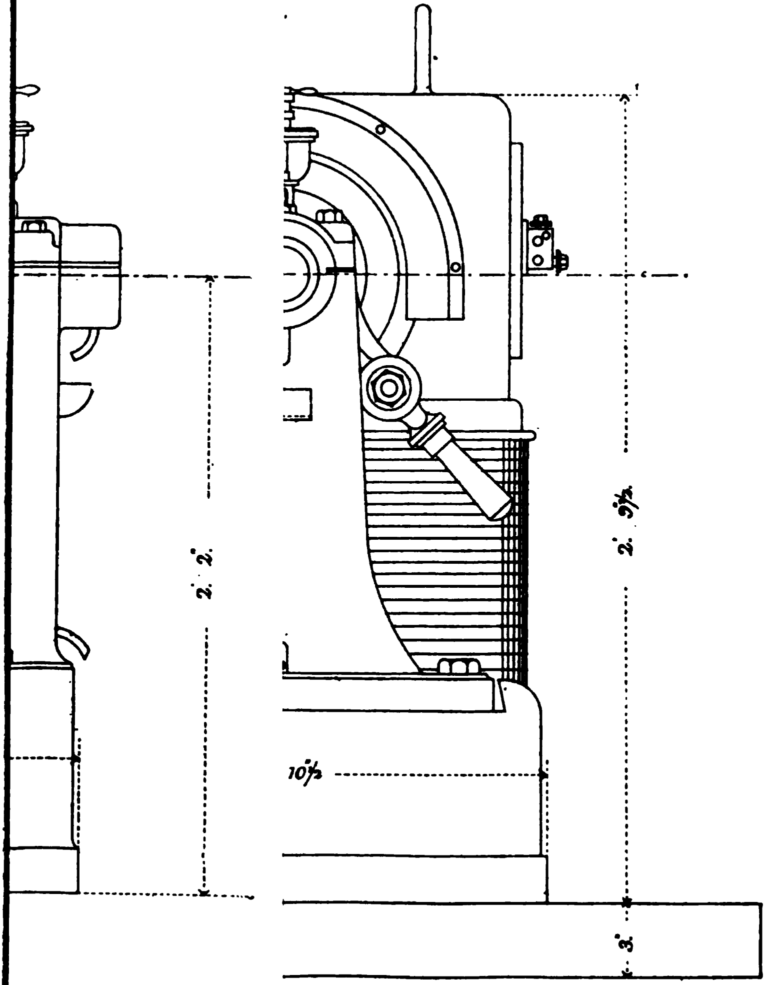

RES AT 100 VOLTS

0 REVS PER MIN.

Plate vii

FIGS I

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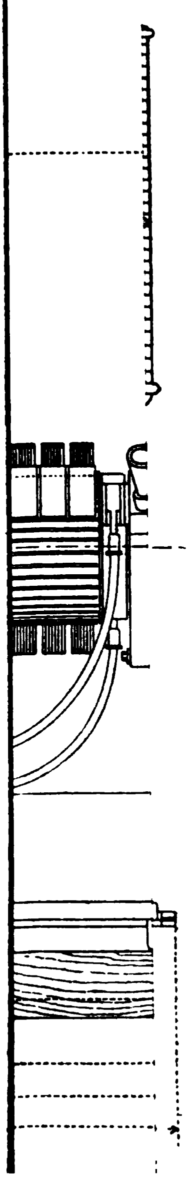

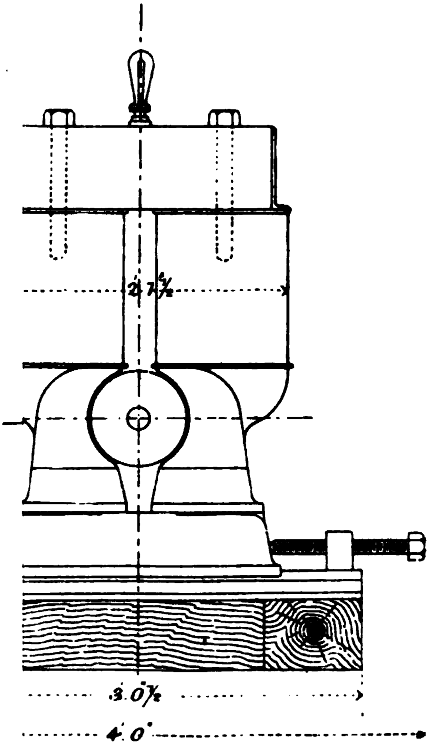

RES AT 140 VOLTS.

RES AT 125 VOLTS.

Plate viii

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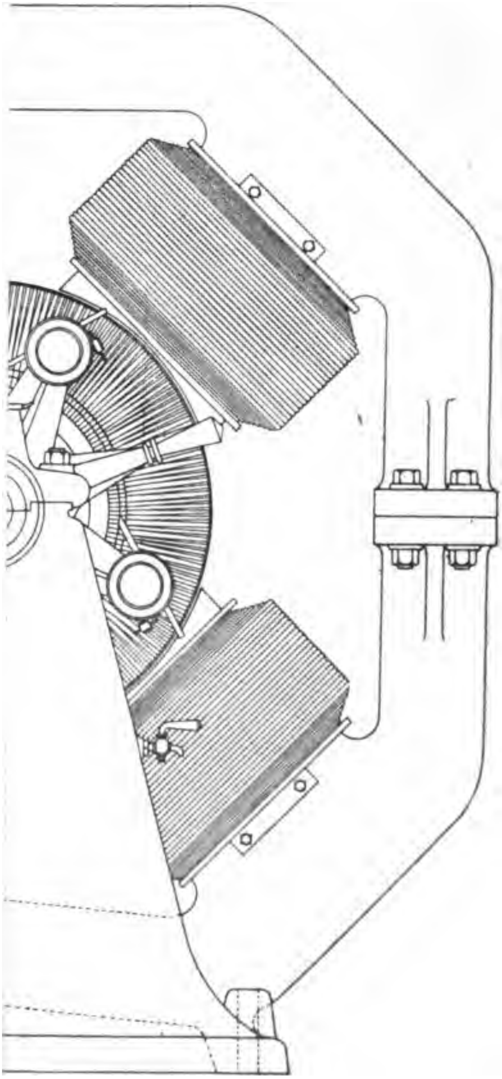


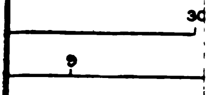
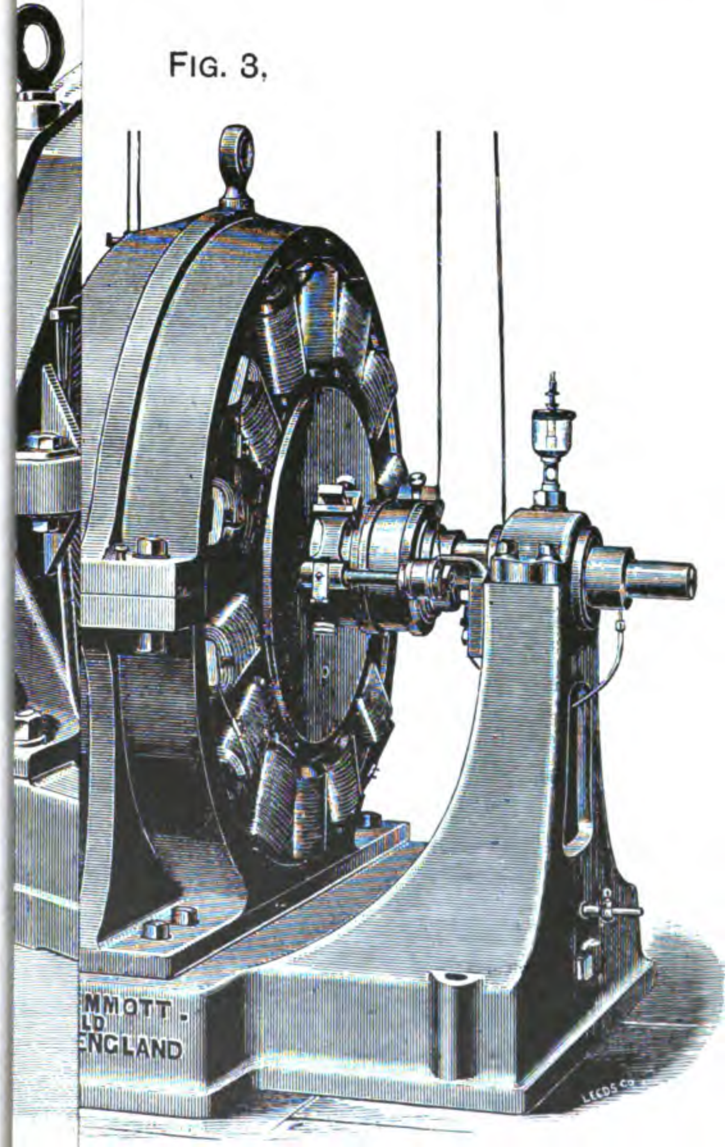


FIG. 3,



S MKEY-EMMOTT ALTERNATOR.

F

Plate x

60 VOLTS.

rich

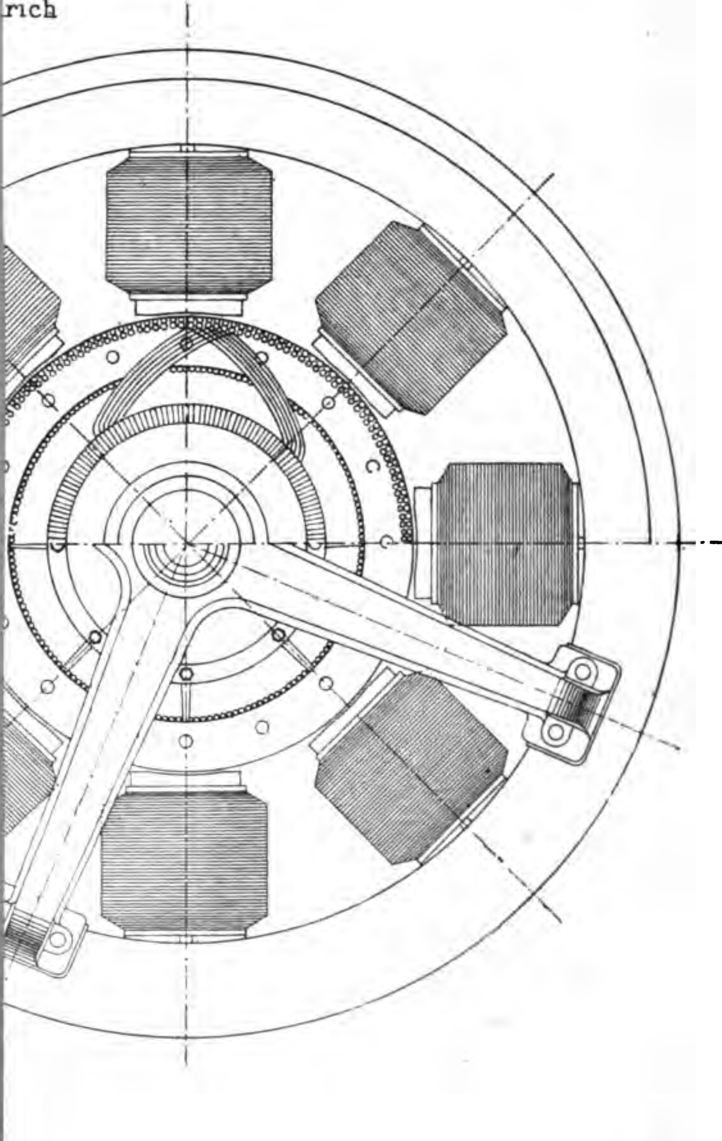
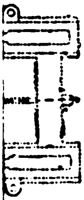
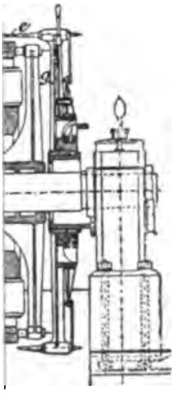
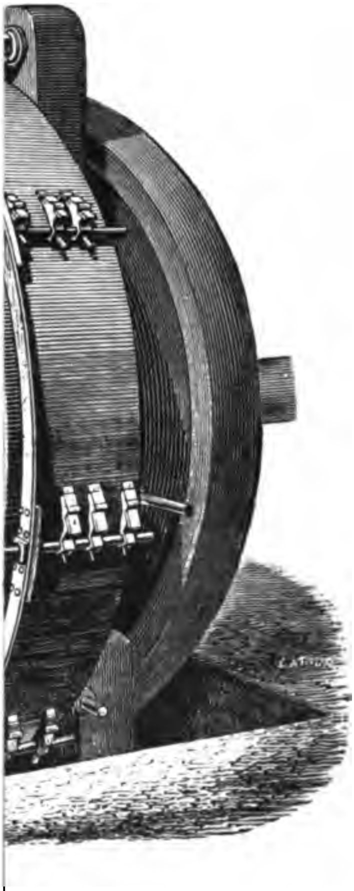


Plate xi







C 600 AMPERES AT 140

Plate xii

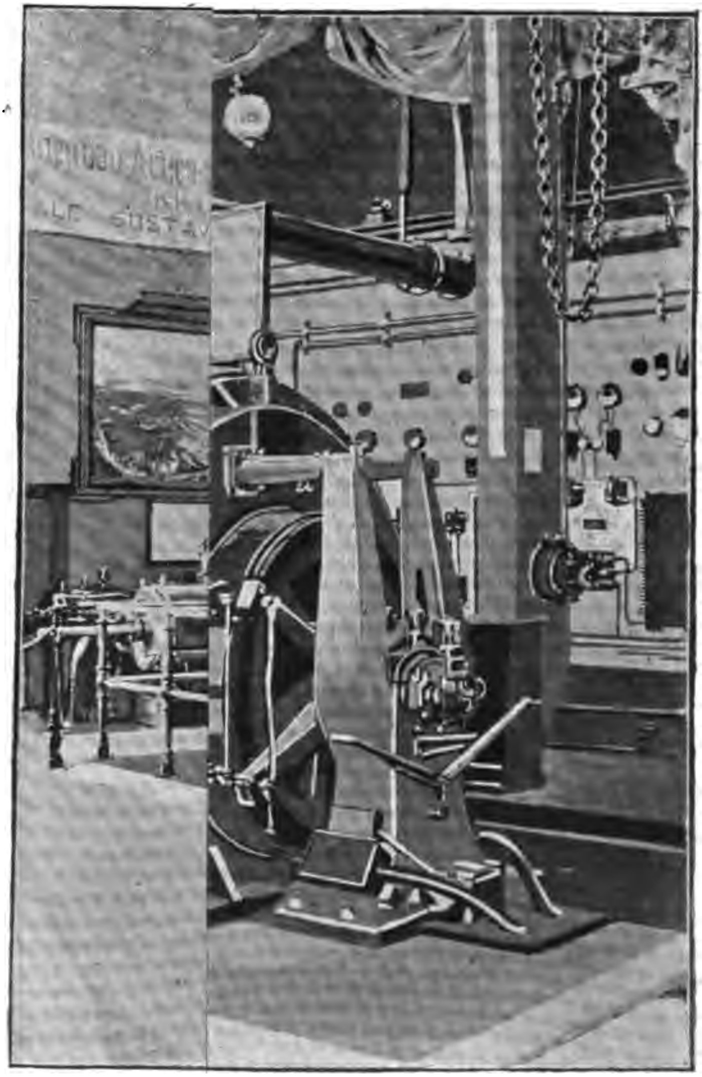


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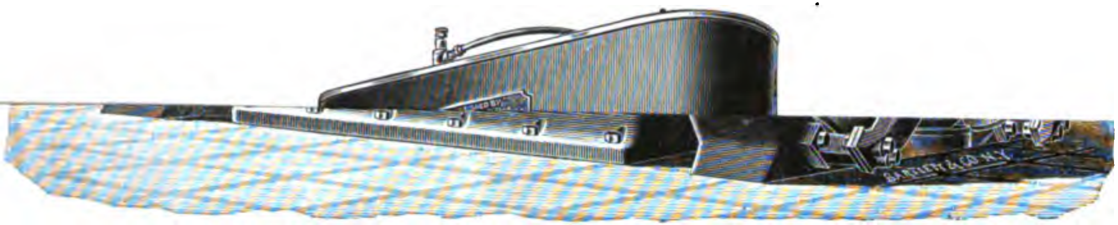
Plate xiii

Note.—The Multipolar Dynamos and Triple Expansion Engine, illustration of which was shown as Plate XIII, in a former edition of this work, has been abandoned and no more machines of that style will be made. The following illustrations show the most recent types of Dynamos and Engines of the General Electric Company.

The above engraving was made from a photograph of the Generator used at the World's Fair, Chicago, and was the largest dynamo manufactured to the date of that event.

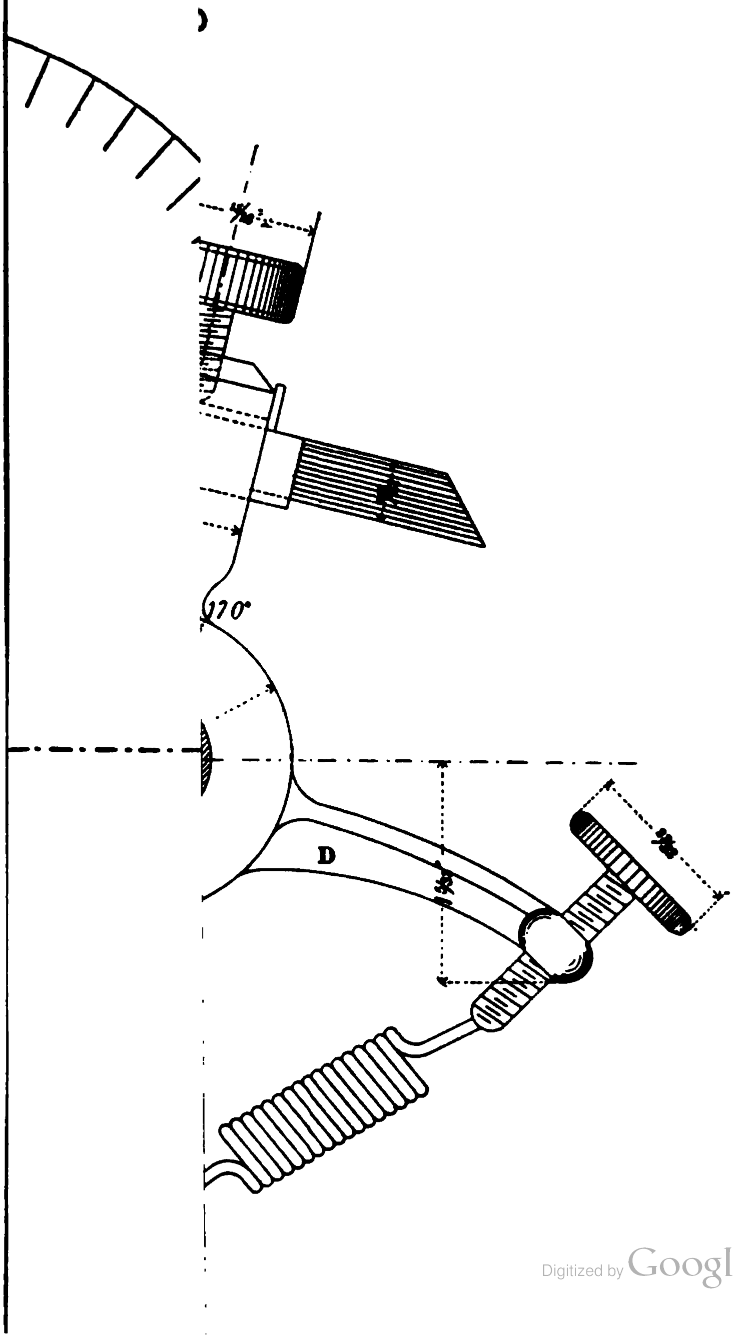

BARTLETT & CO. N.Y.

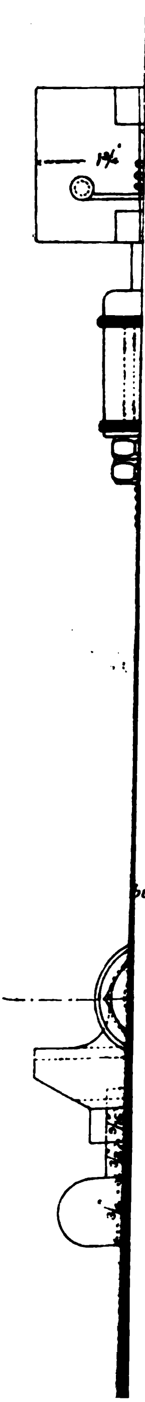
GENERAL ELECTRIC MULTI-POLAR GENERATORS DIRECTLY CONNECTED TO TRIPLE EXPANSION ENGINE.

The combination of Multipolar Generators with the vertical triple-expansion marine type of engine was introduced in 1891, by the General Electric Company, and has been adopted in many stations in the larger cities where economy in real estate investment, belts, etc., and the advantages of better service, have proved considerations of value. The illustration represents two 100 Kilawatt Multipolar Generators, the armatures of which are directly bolted to the crank-shaft of the engine, and in reality act as fly-wheels. The armatures are of the Gramme ring type, built of U shaped copper strips, slipped in a single layer over the laminated wrought-iron core and joined at the ends by a heavier copper bar which acts as a commutator segment. The number of brushes corresponds to the number of poles of the Generator, and are so arranged that they can be operated as a single set by means of a wheel-handle and gear. The field coils are wound on separate spools slipped over the field magnets which are inserted in and bolted to the annular frame of the Dynamo mounted on the bed plate of the engine. The increased diameter of the armature gives a large heat radiating surface. The Generator may be designed to generate any electrical output at a comparatively low armature speed.

The engine is of the triple expansion, three crank, inverted cylinder, automatic condensing type. The forged steel crank-shaft is provided with three eccentrics, each operated by its independent governor, so that the point of cut-off in each cylinder is changed with the load and does away with the tendency to race should the total load be thrown off or an accident occur. These machines are calculated for a maximum efficiency point for about 12 1-2 per cent. below the normal maximum capacity of the generator, and have a range to a maximum capacity of 20 per cent. above the normal maximum output of the generator at 160 pounds initial pressure and vacuum of 24 inches, which allows each engine to operate the generator in condensing. Since this type of dynamo and engine was put out, many important modifications have been made both in dynamo and engine.

Plate xiv

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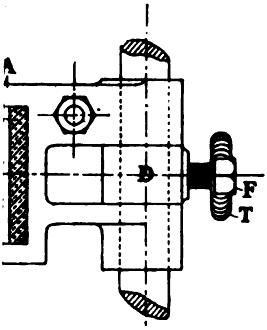
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FIG. 3.

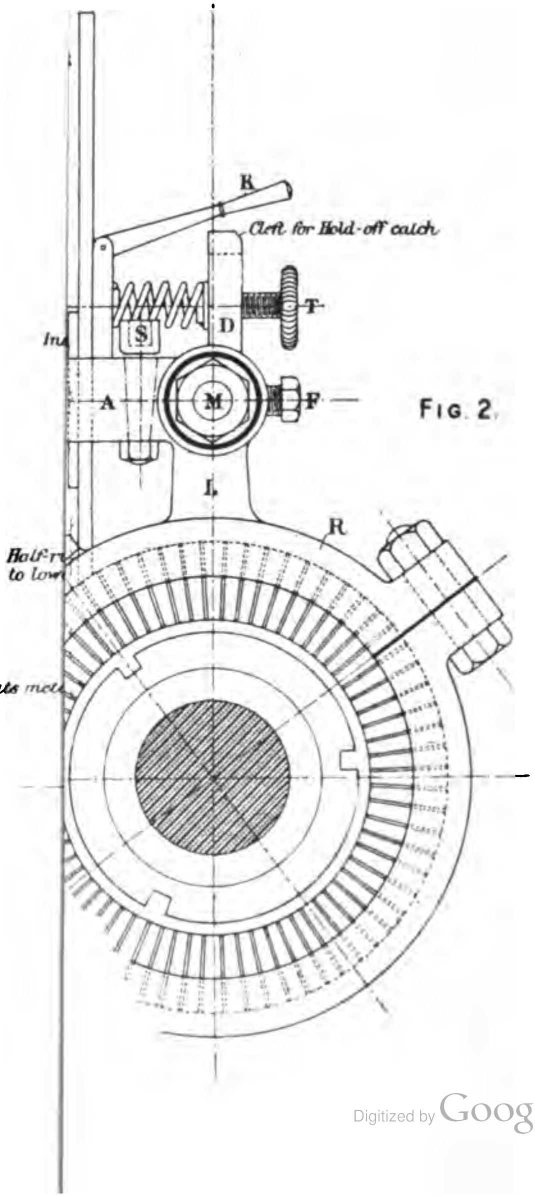
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FIG. 2.